WHERE ARE WE COMING FROM? WHAT ARE WE?
WHERE ARE WE GOING?

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ABSTRACT

The Standard Model is the answer to questions 1 and 2, as established by LEP. Supersymmetry is doubtless the answer to question 3, as may well be established by the LHC.

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1 Answers 1 and 2

The title of this talk is taken from a painting by Paul Gauguin, a reproduction of which was on my office wall for many years. This meeting and most of this talk are devoted to answering the third of Gauguin’s questions. The answer to his first two questions, namely the Standard Model, has been verified by many accelerator experiments, culminating in those at LEP. This provides the bedrock which serves as the foundation for our theoretical attempts to answer the third question, and may be giving us some hints on the correct answer, as I discuss later.

The precision of the LEP results, and these hints, require mastering some very subtle experimental effects. By now, it is relatively well-known that the LEP determination of the $Z$ mass and width depend on the beam energy, which is calibrated using resonant beam depolarization, and is found to be sensitive to the phase of the Moon. The tides it induces cause LEP’s bedrock to expand and contract, affecting the machine’s size and hence its beam energy [1]. So gravity has an effect on LEP - evidence for the unity of physics, if not for the unification of fundamental forces! Less well known, perhaps, is the recent discovery [2] that the LEP beam energy is sensitive to how much it has been raining, as seen in Fig. 1. More water swells the rock and expands the machine. As also seen in Fig. 1, this is also sensitive [3] to the water level in Lake Geneva, albeit with some time delay, much as parts of Northern Europe are still rising after the last Ice Age. These effects account for most of the variations found previously in the LEP beam energy calibration, and further improvements in the precision of the data may be possible now that these are understood.

2 Question 3

Among the questions left unanswered by the Standard Model are the following. What is the origin of particle masses? Are they due to the Higgs mechanism, as expected by theorists? If so, is the Higgs field composite, as in technicolour models? Or is it elementary, in which case is the hierarchy $m_f, M_W, M_H \ll m_P$ protected by supersymmetry? Why are there only three fermion generations, as we have been assured by LEP? What is the origin of the weak mixing angles and CP violation? Are quarks and leptons composite? Or must these questions await answers at the string level? Are the strong and electroweak interactions combined in a Grand Unified Theory below the Planck scale? If so, are neutrino masses and proton decay observable? Are the other particle interactions unified with gravity in some string theory? Does the quantization of gravity entail a modification of the conventional formulations of quantum field theory and quantum mechanics?

Presumably Gauguin’s third question includes all these, and more. I and many other speakers at this meeting would answer these questions within the framework illustrated in Fig. 2. In the following sections, I will discuss the hints from LEP and elsewhere that motivate this framework, and remind you how the LHC, in particular, can help answer Gauguin’s third question.
3 Experimental Hints for Supersymmetry

There are two tentative indications from precision electroweak data, mainly from LEP, that favour the supersymmetric worldview. One is the fact that global fits to the electroweak data tend to favour a relatively light value for the Higgs boson mass: \(M_W \lesssim 300\) GeV as seen in Fig. 3. This is consistent with the range predicted for the mass of the lightest CP-even Higgs boson in the minimal supersymmetric extension of the Standard Model (MSSM): \(M_h \simeq M_Z \pm 40\) GeV \([1]\). Moreover, models of strongly-interacting Higgs sectors, such as calculable technicolour models, are disfavoured by the LEP data. One version of this familiar statement is shown in Fig. 4, where a minimal one-generation technicolour model with \(N_{T_c} = 2\) technicolours and a Majorana technineutrino is confronted with the values of the one-loop radiative-correction parameters \(\epsilon_{1,2,3,b}\) \([8]\) extracted from experiment. An attempt to quantify this discrepancy is made in Fig. 5, where contours of \(\sigma = \sqrt{\chi^2}\) (corresponding roughly to the number of standard deviations) are plotted for one-generation \(N_{T_c} = 2\) models with either a Dirac or Majorana technineutrino: we see that \(\sigma > \sim 5\) in both cases.

There has been some discussion at this meeting of the new estimates of \(\alpha_{em}(M_Z)\), some of which differ significantly from the previous best estimates used in the above analyses of \(M_H\) and technicolour models. We have made an exploratory study of the possible implications of this increase in \(\alpha_{em}(M_Z)^{-1}\). In general, an increase in \(1/\alpha\) corresponds to a decrease in \(\sin^2 \theta_{eff}\), other thing being equal. In fact, LEP and other experiments essentially fix \(\sin^2 \theta_{eff}\), so this effect must be compensated by a decrease in \(m_t\) and/or an increase in \(M_H\) and/or a decrease in \(\alpha_s(M_Z)\). We have found that in an \(\epsilon_{1,2,3,b}\) analysis a fit using just the LEP data, \(M_W\) and the old \(\alpha_{em}(M_Z)^{-1} = 128.87(12)\) is indistinguishable from a fit including also the SLC \(A_{LR}\) measurement and \(\alpha_{em}(M_Z)^{-1} = 129.08(10)\). As can be seen in Fig. 3, including \(A_{LR}\) increases \(M_H\) somewhat, but small values are still preferred.

The second LEP hint for supersymmetry is provided by the well-publicized consistency of \(\sin^2 \theta_W\) with minimal supersymmetric GUTs \([10]\). It is true that the minimal non-supersymmetric GUT prediction \([11]\)

\[
\sin^2 \theta_W(M_Z)_{\overline{MS}} = 0.208 + 0.006 \ln \left( \frac{400 \text{ MeV}}{\Lambda_{\overline{MS}}(N_f = 4)} \right) = 0.214 \pm 0.004
\]

(1)

can be excluded. However, the supersymmetric GUT prediction is less precise, since it has more parameters. As I discuss later, this means one cannot use the value of \(\sin^2 \theta_W\) to constrain significantly the masses of supersymmetric particles.

4 Experimental Constraints on the MSSM

Let us now discuss the present direct and indirect constraints on the parameters of the MSSM. Indirect constraints come from the precision electroweak data discussed earlier, now reanalyzed using MSSM quantum corrections \([3]\). Figure 6 shows that fits in the MSSM for a given value
of $M_h$ have values of $\chi^2$ very similar to those in the Standard Model for the same value of $M_H$. However, one essential difference is that only a restricted range of $M_h$ is allowed in the MSSM. Figure 7 shows $\Delta \chi^2 = 1$ contours for fits to various different selections of electroweak data, as well as the bounds on $M_h$ for two values of $\tan \beta$, the ratio of MSSM Higgs v.e.v.'s. The $\Delta \chi^2 = 1$ curves are themselves almost independent of $\tan \beta$ within the corresponding physical regions. Notice that in these fits large values have been assumed for $\mu, m_0$ (supposed to be universal) and $m_{\tilde{g}}$, so that sparticles essentially decouple.

We have also explored [3] the indirect electroweak constraints on $m_0$ and $m_{\tilde{g}}$ (or equivalently $m_{3/2}$), as seen in Fig. 8. These are compared with the direct LEP and CDF search limits [12] for the same choice of $\mu, m_A$ and $\tan \beta$. We see that the indirect constraints may be competitive in some regions of the $(m_0, m_{\tilde{g}})$ plane. LEP 2, due to operate in the years 1996 to 1999, should essentially double the present direct LEP lower limit on $m_{\tilde{g}}$, and the CDF direct lower limit on $m_{\tilde{g}}$ should increase to between 300 to 350 GeV within the next few years. The CDF limits in Fig. 8 are from a missing energy search: in the future, useful limits may also be obtained from searches for the decays of electroeakly-interacting sparticles into trilepton final states [13].

5 The Importance of the LHC

It is clear that the full MSSM parameter space cannot be explored before the advent of the LHC. The decision to approve the LHC was taken during this meeting, and it is clear that my answers to Gauguin’s questions would have been much less optimistic if it had not been approved. The approval is for an initial energy of 10 TeV, but I assume that sufficient non-Member-State support will become available for the machine to start at the design energy of 14 TeV. CERN’s planning foresees at least four experiments in the initial LHC programme: two pp discovery physics experiments ATLAS [13] and CMS [14], an experiment dedicated to CP violation in $B$ decays [17], and an experiment ALICE [16] to look for quark-gluon plasma formation in heavy-ion collisions. There may in addition be an experiment to look for diffractive scattering [17], and ideas [18] for neutrino experiments are under active discussion.

Figure 9 demonstrates that the ATLAS experiment [13] should be able to detect strongly-interacting sparticle pair production in the missing energy channel for $m_{\tilde{g}} \lesssim 1500$ GeV. The total Standard Model background is not a problem for missing transverse energies above about 500 GeV, and the instrumental background is also expected to be negligible in this range. Similar sensitivity is to be expected in the CMS experiment [14]. Thus essentially all the parameter space of the MSSM allowed by naturalness arguments will be covered. If the LHC does not discover supersymmetry, we theorists will have to eat our collective hat.

The prospects of finding the MSSM Higgs sector at the LHC are less clear [19]. As is well known and quite visible in Fig. 10a, which shows the regions of the $(m_A, \tan \beta)$ plane accessible to the CMS experiment [14], there is a troublesome region $100$ GeV $\lesssim m_A \lesssim 250$ GeV, $2 \lesssim \tan \beta \lesssim 10$ where it will be difficult to discover any of the MSSM Higgs bosons. As is seen in
Fig. 10b, the ATLAS collaboration \cite{13} reckons that it may ultimately be sensitive in all of the $(m_A, \tan\beta)$ plane. However, there is little safety margin, and this problem requires more study.

Before leaving the LHC, in view of the interest at this meeting in $B$ physics, it is worth mentioning the physics reach of the LHC for CP violation in $B$ decays \cite{15}. Figure 11 shows as a solid line the present-day constraints on the CP-violating observables $\sin 2\beta$ and $\sin 2\alpha$ inferred from our knowledge of the CKM matrix \cite{20}, and the dashed line indicates how the constraints may improve by the year 2000. Also shown are the likely errors in an $e^+e^- B$-meson factory experiment \cite{21}, and what could be attainable at the LHC \cite{13}. With error bars as small as these, in the next decade flavour physics may become as powerful in testing the Standard Model and constraining its possible extensions as are precision electroweak data today.

6 Supersymmetry and GUTs

The success \cite{10} of the supersymmetric GUT prediction for $\sin^2\theta_W$ has already been mentioned. Now I would like to address the question whether this success constrains usefully the supersymmetry breaking parameters of the MSSM. At the two-loop level, neglecting the uncertainty due to GUT threshold effects and retaining just the light thresholds, one has \cite{22}

$$\sin^2\theta_W(M_Z) \bigg|_{\overline{MS}} = 0.2029 + \frac{7\alpha_{em}}{15\alpha_3} + \frac{\alpha_{em}}{20\pi} \left[ -3 \ln \left( \frac{m_t}{M_Z} \right) + \frac{28}{3} \ln \left( \frac{m_3}{M_Z} \right) - \frac{32}{3} \ln \left( \frac{m_W}{M_Z} \right) - 4 \ln \left( \frac{M_H}{M_Z} \right) - 4 \ln \left( \frac{\mu}{M_Z} \right) + \frac{3}{8} f \right]$$

where $f$ depends on ratios of supersymmetry breaking parameters and is about $0.2 \pm 0.2$, and hence less important numerically than the other parameters in (2). The relatively precise supersymmetric GUT prediction for $\sin^2\theta_W(M_Z) \bigg|_{\overline{MS}}$ that is often quoted makes the assumption that the unknown MSSM parameters are equal to $M_Z$, or some similar assumption. One can invert (2) to obtain an expression for the supersymmetry-breaking gaugino mass parameter $m_{1/2}$:

$$\ln \left( \frac{m_{1/2}}{M_Z} \right) = \frac{15\pi}{\alpha_{em}} \left[ 0.2029 + \frac{7\alpha_{em}}{15\alpha_3} - \sin^2\theta_W(M_Z) \bigg|_{\overline{MS}} - \frac{9}{4} \ln \left( \frac{m_t}{M_Z} \right) - \frac{3}{4} \ln \left( \frac{M_H}{M_Z} \right) - 3 \ln \left( \frac{\mu}{M_Z} \right) + 8.839 + \frac{3}{8} f \right]$$

Uncertainties in the quantities on the right-hand side of (3), particularly but not exclusively $\alpha_3(M_Z)$, prevent \cite{22}, \cite{23} one from quoting a meaningfully narrow range for $m_{1/2}$, even if GUT threshold effects can be neglected, which is probably not the case. Nevertheless, the qualitative agreement with experiment of the minimal supersymmetric GUT prediction remains impressive circumstantial evidence for supersymmetric GUTs.
7 GUTs, Neutrino Masses and Baryogenesis

There has been much discussion at this meeting of solar neutrino data and their interpretation in terms of neutrino oscillations. I certainly share the impression that astrophysics alone cannot accommodate the apparent deficits found by all the solar neutrino experiments, and find the MSW matter-enhanced neutrino oscillation interpretation \[24\] with

\[
\Delta m^2_\nu \sim 10^{-5} \text{ eV}^2, \quad \sin^2 2\theta_\nu \sim 10^{-2}
\]

the most natural. Perhaps these are the first direct indications of physics beyond the Standard Model?

Theoretically, the most appealing model for neutrino masses is the GUT see-saw matrix:

\[
\begin{pmatrix}
\sim 0 & m_f \\
 m_f & M_M
\end{pmatrix}
\]

(5)

where \(M_M\) is a Majorana mass for the right-handed neutrino. This suggests that

\[
m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} \sim m_u^2 : m_e^2 : m_t^2
\]

(6)

assuming there is not a large hierarchy in the \(M_M\) for different generations, in which case the MSW solution (4) suggests that

\[
m_{\nu_e} \ll m_{\nu_\mu} \sim (2 \text{ or } 3) \times 10^{-3} \text{ eV}
\]

(7)

Scaling this up by \(m_t^2/m_e^2\), it appears perfectly reasonable to expect that

\[
m_{\nu_e} \sim 10 \text{ eV}
\]

(8)

as advocated by enthusiasts for a component of Hot Dark Matter.

If this model is correct, evidence for it may soon be found in accelerator experiments. The two CERN experiments (CHORUS and NOMAD) designed to look for \(\sin^2 \theta_{e\mu} \gtrsim 10^{-4}\) when \(\Delta m^2_{\nu_e,\nu_\tau} \sim 10^2 \text{ eV}^2\) are now operating, and many GUT see-saw models predict \(\nu_\mu - \nu_e\) mixing angles within their range of sensitivity \[25\]. Will they provide the first laboratory evidence for physics beyond the Standard Model?

If the estimate (8) is correct, and we use (6) with \(m_t \sim 170 \text{ GeV}\), we need \(M_M \sim 10^{12} \text{ GeV}\) for the third-generation right-handed neutrino mass. This is considerably below the supersymmetric GUT scale of \(10^{16} \text{ GeV}\), but the appearance of right-handed neutrinos in this mass range would not upset the calculation of \(\sin^2 \theta_W(M_Z) \bigg|_{\text{MS}}\), since they \(SU(3) \times SU(2) \times U(1)\) gauge singlets. Indeed, such a value of \(M_M\) could be boon to cosmological baryogenesis.

To my mind, the most elegant scenario \[26\] for this is \(\nu_R \rightarrow L + H\) decay producing a net lepton asymmetry \(\Delta L \neq 0\), which is then recycled by non-perturbative electroweak effects with \(\Delta(B - L) = 0\) to yield finally a net baryon asymmetry \(\Delta B \neq 0\). This works only if the
\( \nu_R \) are produced after inflation, which requires inflaton \( \Phi \rightarrow \nu_R \) decay, and hence \( M_M < m_\Phi \).

The COBE observation of fluctuations in the microwave background radiation suggests that \( m_\Phi \sim 10^{13} \) GeV, in which case \( M_M \lesssim 10^{12} \) GeV is required, and the neutrino masses cannot be much smaller than the astrophysically-preferred values (7), (8). Thus the MSW interpretation of the solar neutrino data is compatible not only with the \( \nu_\tau \) constituting a Hot Dark Matter component, but also with neutrino baryogenesis [27].

8 Answer 3: Superstring

This is the only candidate we have for a Theory of Everything, including quantum gravity, and hence for our ultimate destination beyond the Standard Model. However, as you know, there is considerable ambiguity in the choice of string model, and hence a frustrating ambiguity in its experimental predictions. In the past, people have constructed string models based on non-unified gauge groups such as \( SU(3)^3 \) [28], \( SU(3) \times SU(2) \times U(1)^n \) [29] and \( SU(5) \times U(1)^m \) [30]. The latter flipped \( SU(5) \) model has been my personal interest: it is the closest to a conventional GUT that can be constructed without using a higher-level representation of the Kac-Moody current algebra on the world sheet [31]. Progress has recently been made in formulating higher-level models [32]. Though a completely realistic example has yet to emerge, it may be possible in this way to construct a realistic superstring GUT. I will not enter into specific models here, but conclude this talk by reminding you of two interesting qualitative predictions of string models that are relatively model-independent.

One is the calculation [33] of the string unification scale, i.e., the energy at which the extrapolated low-energy gauge couplings should appear to become equal, which is

\[
M_{SU} \simeq 5 \times g \times 10^{17} \text{ GeV } \times F \tag{9}
\]

where \( g \) is the gauge coupling and \( F \) depends on the specific string model chosen, which is about unity in models constructed out of free world-sheet fermions [34]. The prediction (9) appears to be somewhat larger than the minimal supersymmetric GUT calculation of about \( 10^{16} \) GeV. Perhaps we should look at models with \( F < 1 \), or perhaps we should look at models with additional light particles, or perhaps the GUT unification scale really is below below the string unification scale, as occurs in flipped \( SU(5) \). It is encouraging that string at least gives us a unification scale of a sort.

The second qualitative string prediction I would like to emphasize is that for \( m_t \). It is a generic feature of models derived from string that non-zero Yukawa couplings \( \lambda \) are of the same order as the gauge coupling [33], specifically, in free-fermion models such as flipped \( SU(5) \) [30]

\[
\lambda = \sqrt{2} g \tag{10}
\]

If applied to the top quark Yukawa coupling, this yields after renormalization a value of \( m_t \) below but close to the approximate infrared fixed point:

\[
m_t \simeq 190 \sin \beta \text{ GeV} \tag{11}
\]
in the case of free fermion models. Not such a bad prediction! There are many other interesting ideas circulating about Yukawa unification [36] and the possible dynamical determination of the top and other quark masses [37], which I do not have time to discuss here.

Physicists sometimes despair of ever being able to prove that string is the answer to Gau- guin’s third question, even if it is. These two examples may serve as some encouragement that testing string may not be impossible, even in the absence of direct probes of quantum gravity.
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FIGURE CAPTIONS

Fig. 1 - Sensitivity of the LEP beam energy to (a) tides [1]: the solid lines are due to a tidal model, (b) the water table in the Jura mountains and (c) the level of Lake Geneva [2].

Fig. 2 - The supersymmetric worldview answers Gauguin’s third question.

Fig 3 - Contours of $\Delta \chi^2 = 1$ in the $(M_H, m_t)$ plane for a Standard Model analysis [3] of all electroweak data (ALL), including (+) or not (-) the SLD measurement of $A_{LR}$ (ALR) and the CDF kinematic fit to $m_t$ (CDF). The $\Delta \chi^2 = 1$ bands allowed by CDF and ALR alone are shown separately. For ALL$^{+\text{CDF}}_{-\text{ALR}}$ fit, which combines the LEP, CDF and low energy data, the $\Delta \chi^2 = 4(2\sigma)$ contour is also shown.

Fig. 4 - Comparison [6] of the Born approximation (stars), projections of the $\Delta \chi^2 = 1, 4$ ellipsoid (solid ellipses), the SM (grid) and the predictions of a one-generation TC model with $N_{TC} = 2$, a Dirac technineutrino, $M_U = M_D$, $100 \text{ GeV} < M_E < 600 \text{ GeV}$, $50 \text{ GeV} < M_N < M_E$ (scattered dots). The TC predictions are added to the SM radiative corrections, using the reference values $m_t = 170 \text{ GeV}$ and $M_H = M_Z$. Note that the TC predictions are further than the SM from the experimental data. The bold arrows labelled TQ and B indicate possible shifts in the TC predictions of definite sign, and the other (thin) arrows labelled B and NC indicate shifts that are less certain.

Fig. 5 - Contours [6] of $\sigma \equiv \sqrt{\Delta \chi^2}$ for one-generation models with either Dirac technineutrinos (a), (b) or Majorana technineutrino (c), (d). Note that $\sigma \gtrsim 4.5$ in all of the TC parameter space, to be compared with $\sigma = 2.6$ in the SM at the reference point ($m_t = 170 \text{ GeV}$, $M_H = M_Z$). In the case of techniquark mass degeneracy ($M_U = M_D$), the Dirac and Majorana models fits are comparable; in the case $M_U > M_D$, however, the Dirac model becomes highly disfavoured.

Fig. 6 - Curves of $\chi^2$ as function of the (lightest) Higgs boson mass in the Standard Model (dashed line) and the MSSM (solid line) at $m_t = 150, 170, 190 \text{ GeV}$, using ALL$^{+\text{CDF}}_{-\text{ALR}}$ data [3]. In the MSSM case we choose $\tan \beta = 4, \mu = m_{\tilde{g}} = m_0 = 1 \text{ TeV}$. Notice that the dashed and solid curves are very close and finally merge when $m_h$ reaches its theoretical upper limit.

Fig. 7 - Contours of $\Delta \chi^2 = 1$ in the $(m_h, m_t)$ plane for an MSSM analysis [3] of all electroweak data (ALL), including (+) or not (-) the SLD measurement of $A_{LR}$ are set to large values by choosing $\mu m_\tilde{g} = m_0 = 1 \text{ TeV}$. Also shown are the theoretical lower and upper bounds on $m_{\tilde{h}}$ for $\tan \beta = 2$ and 16, corresponding to $m_A = 0, \infty$. Actually each curve is slightly dependent on $\tan \beta$ within the allowed range; the difference is however negligible for our purposes, and a smoothed average is shown.

Fig. 8 - Exclusion plot [3] in the $(m_0, m_{\tilde{g}})$ plane for $m_t = 165 \text{ GeV}$, $\mu = 250 \text{ GeV}$, $m_A = 500 \text{ GeV}$, $\tan \beta = 2$. The solid curve labelled “MSSM R.C.” encloses the region excluded by our ALL$^{+\text{CDF}}_{-\text{ALR}}$ fit (with MSSM radiative corrections) at $\Delta \chi^2 = 2.7$ (90% C.L. on each variable separately). Also shown are the limits on slepton and chargino masses from LEP, and the exclusion contours from the negative results of CDF searches for gluinos and squarks (CDF solid line: with cascade decays; CDF dashed line: no cascade decays; the cusp corresponds to the case $m_{\tilde{g}} = m_{\tilde{g}}$). Notice that the region just above the chargino threshold $M_Z/2$ is here excluded both by CDF and the MSSM R.C. analysis (assuming the standard mass relations in the MSSM).

Fig. 9 - Missing-energy signature of squarks and gluinos in the ATLAS [13] detector (histogram) compared with the physics background (open circles), naïve estimate of instrumental background (solid squares) and more realistic estimate (open triangles).
Fig. 10 - Search for MSSM Higgs bosons in the $(m_A, \tan \beta)$ plane with (a) CMS [14], (b) ATLAS [13].

Fig. 11 - Present and possible future constraints within the Standard Model on the CP-violating parameters $(\alpha, \beta)$ that are measurable in $B$ decays [20], compared with the superweak theory prediction and possible future measurement errors.
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