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CERN-TH.6723/92

UNIFICATION AND PLURALISM IN THEORETICAL PHYSICS

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*Based on concluding talk presented at the First CERN-Torino Meeting on
Current Trends in Particle and Condensed Matter Physics, Torino, May 11 to
13, 1992*

CERN-TH.6723/92
November 1992

1 - HISTORY AND GEOGRAPHY

When I was at school during the 1960's in England, one of the great intellectual debates of the time was about the "Two Cultures". Its principal protagonists were the scientist and administrator C.P. Snow and the humanist F.R. Leavis. To caricature the complexity of their views in one sentence: Snow bemoaned the apparent separation of Science and the Arts into two separate cultures, whereas Leavis accepted this as an inevitable consequence of the generic barbarism of scientists.

The chief organizer and inspiration of this meeting [1], Sergio Fubini, has recently in an essay written for Luigi Radicati reminded us of this debate, and resurrected it in the context of Particle Physics in the 1990s. To caricature his views also in one sentence: he bemoans the apparent separation of Theoretical Physics into two separate cultures, one involved in the phenomenological analysis of experimental data, principally from accelerators, and the other more abstract, closely connected with Mathematics and seemingly unconcerned with experimental tests. One of his principal objectives in organizing this meeting was to combat this trend by bringing together phenomenologists and more abstract theorists working on Gravity and on Condensed Matter Physics. Nobody here has spoken against this laudable objective, but anonymous theorists have voted with their feet, as summarized in the following formula:

$$(1 \cup 3) \cap (2) = \emptyset \quad (1)$$

where the numbers symbolize the communities of theorists active on the corresponding days of the meeting. However, on the first day we did succeed in having a very lively and wide-ranging communal debate on the fundamental problems in Quantum Gravity, and the extent to which string theory may solve (or has solved) them. This is already a step forward from the sterile invective sometimes hurled at string theory by some phenomenological theorists elsewhere.

In this talk I review some of the links between the more phenomenological and theoretical directions in Physics discussed at this meeting, and suggest some of the principal trends which are important now and likely to be so in the future. I seek to emphasize not only that theory and phenomenology are intimately linked, but also that Gravity, Particle Physics and Condensed Matter Physics are now more intimately linked than they used to be for some time. I also make a plea for confidence in the underlying unity of Physics, and tolerance towards those whose interests are not transparently connected to yours. Even if a direct connection is not apparent now, history teaches us that one may well appear soon.

Figure 1 sketches the geography of Theoretical Physics and its neighbours, Experimental Physics and Mathematics. Centre left, in order of decreasing

energy, we have the classes of physical problems discussed at this meeting, and centre right, in order of decreasing dimensionality, we have the field-theoretical framework discussed here. Far left, we have Experiment, whose strength of connection with the physical problems is somewhat inversely proportional to the corresponding energy and hence cost of doing experiments: effectively infinite in the case of Quantum Gravity! On the far right we have Mathematics, which is not only exploited but also frequently developed by theoretical physicists, witness Dirac's distribution theory in an earlier time, and more recently the Virasoro algebra and its higher-spin extensions discussed below. The arrows across the centre of Figure 1 represent the connections between theory and phenomenology that were made during this meeting. In the subsequent sections of this talk I will combine many of the arrows into "quivers" categorizing important common themes.

2 - RENORMALIZATION GROUP

This is a calculational tool that has long been passed backwards and forwards between Particle and Condensed Matter Physics. First discovered in Particle Physics by Stueckelberg, Petermann, Gell-Mann and Low, it was given a very physical interpretation by Fisher and Kadanoff in the context of Condensed Matter Physics. Then, two theorists with backgrounds in Particle Physics, first Wilson and then Polyakov, showed how to apply it to make quantitative predictions for second-order phase transitions in Condensed Matter Physics.

Applications of the renormalization group to Particle Physics have usually been in the ultra-violet limit, e.g. in QED to find the Landau pole, in QCD to find that there was no Landau pole but asymptotic freedom instead, and in the electroweak sector to extrapolate gauge couplings, measured most precisely at LEP, to higher energies to see test consistency with some Grand Unified Theory (GUT). Some of the most elegant confirmation of asymptotic freedom has also come from LEP [2], as seen in Figure 2, which shows the energy-dependence of a measure of the 3-jet cross-section that is proportional to the strong coupling α_3 . It is by now well known that the extrapolation of data on α_3 and the electroweak couplings α_1 and α_2 to energies a mere 13 orders of magnitude greater finds an inconsistency with non-supersymmetric GUTs. This discrepancy existed already before LEP [3] but is now much more significant [4], whilst the data are highly consistent with supersymmetric GUTs.

A close-up view of this consistency is shown in Figure 3, where you see that minimal non-supersymmetric GUTs are indeed apparently doomed. However, whether you believe that minimal supersymmetric GUTs with a common supersymmetric particle threshold at m_Z agree perfectly with the data, or not, depends on the range of values of α_3 that you believe. The converse of this statement is shown in Figure 4, which shows the range of values of the supersymmetry breaking scale, taken to be a primordial unified

gaugino mass, which is consistent with any given value of $\alpha_3(m_Z)$ [5]. We see that the range $m_{1/2} < 1$ TeV expected on the basis of the naturalness of the GUT hierarchy is consistent only with $\alpha_3 < 0.115$, whereas most recent LEP determinations prefer $\alpha_3 \sim 0.120$. Time will tell whether we should turn towards non-minimal supersymmetric GUTs such as a string-derived flipped SU(5) model [6].

As already mentioned, these GUT calculations have traditionally been viewed in the bottom-up, ultra-violet direction, starting from accelerator inputs of the different Standard Model gauge couplings, and extrapolating bravely to much higher energies. The typical applications of the renormalization group to Condensed Matter Physics, on the other hand, have been in the infra-red limit, already in the description of critical phenomena and second-order phase transitions, and now possibly the quantum Hall effect. However, with the advent of string theory as a Theory of Everything (TOE) including Quantum Gravity, now the GUT calculation mentioned above is also best viewed in the top-down, infra-red direction. In any given string model, it is possible [7] to make a first-principles calculation of the scale m_U at which the extrapolated low-energy couplings should appear to come together, and relate it to the Planck Mass:

$$m_U = (mp / (\sqrt{8\pi})) \times F(\text{moduli, matter fields}) \quad (2)$$

We [8] have suggested that the confrontation between the bottom-up calculation of m_{GUT} and the top-down value (2) may mark the debut of "Moduli Phenomenology" - a rather different example of this concept may be in the Quantum Hall Effect discussed later! In string models formulated using free fermions on the world-sheet, $F \simeq 1$, and the bottom-up and top-down calculations of the unification scale apparently disagree [8]. It could be, however, that unification occurs in two stages as in flipped SU(5) [5], where α_2 and α_3 become equal at m_{GUT} to α_5 , and α_5 subsequently becomes equal to α_1 at m_U . In the flipped SU(5) model one would then expect $\sin^2\theta_W$ to be somewhat lower than in a minimal SU(5) GUT, which is not inconsistent with the data mentioned above. Alternatively, it could be that $F \simeq 10^{-2}$, perhaps in some Z_N or $Z_N \times Z_M$ orbifold model although not all values of N allow this possibility [9].

The top-down calculation (2) of m_U is just one application of the renormalization group to a problem in Quantum Gravity, which previously was not a player in the renormalization group game, because gravity was not a renormalizable theory. This has changed, however, with the advent of string theory as a TOE. Another application of the renormalization group to Quantum Gravity within the framework of string theory is to two-dimensional theories on the world-sheet, where Zamolodchikov's c-theorem [10] may give us insight into the effective string theory that describes at least our part of the Universe.

3 - SYMMETRIES AND SYMMETRY BREAKING

In Condensed Matter Physics, the symmetry whose breaking is of interest is the local U(1) of QED. Among the key names associated with the relevant spontaneous symmetry-breaking mechanisms are Nambu and Goldstone (NG) in more than 2 dimensions, Berezinsky, Kosterlitz and Thouless (BKT) in 2 dimensions, Landau and Ginzburg (LG), and of course Bardeen, Cooper and Schrieffer (BCS). In the familiar BCS theory applicable to low- T_c superconductivity, there is a composite condensate of Cooper pairs $\phi = e^-e^-$ in the ground state (vacuum), bound together by phonons (lattice vibrations). However, one should doubt whether the same mechanism describes high- T_c superconductors, which are approximately planar systems, since the global symmetry breaking mechanisms in two dimensions (KT) and more (NG) are different. In 2+1-dimensional systems there can exist anyons [11], particles with arbitrary statistics intermediate between bosons and fermions, which are also able to condense and lead in principle to superconductivity. Anyons may also play a role in the quantum Hall effect, which appears in planar electron systems. They are among the objects now studied by some particle physicists taking an interest in Condensed Matter Physics, as we shall discuss later.

In Particle Physics, the symmetry whose breaking is currently of interest is the local $SU(2) \times U(1)$ of the electroweak sector of the Standard Model. It is presumably broken spontaneously by some variant of the Higgs/Kibble/Anderson/Brout et al. mechanism. There is now an intense debate whether the symmetry-breaking order parameter is composite as in Condensed Matter Physics, such as a tt [12] or Technicolour [13] condensate, or whether it is elementary. The latter appears to me to be a much more radical and novel hypothesis, requiring the postulation of a new type of symmetry not previously seen at the fundamental level, namely supersymmetry. Later in this talk, some of the ways in which LEP starts to discriminate among these electroweak symmetry-breaking mechanisms will be discussed. Beyond the Standard Model, there are presumably higher symmetries to be broken spontaneously, such as the GUT symmetry [SU(5) or ...?] and/or supersymmetry itself, but I will not discuss them here.

In Quantum Gravity, the situation is much less clear, and discussions of the relevant symmetry and how it is broken are only just starting. However, it seems that an infinite-dimensional local symmetry must be at work, at least in the context of string theory. At the end of this talk will be mentioned some ideas about the stringy symmetry of Gravity and its breaking, which could perhaps even be probed by searches for CP and CPT violation in Particle Physics experiments at the DAFNE accelerator!

Let us now review some common aspects of modern approaches to these symmetry-breaking problems.

Quantum Hall Effect: Experiments observe integer and fractional plateaux in the transverse planar conductivity σ_{xy} [14]. The favoured interpretation [15] of this effect invokes anyons within a hierarchy generation scheme in which each level is a condensation of the previous level, which yields the relation

$$A: \sigma_{xy} \rightarrow \sigma_{xy}/(1 + \sigma_{xy}) \quad (3a)$$

whilst particle $\leftrightarrow$ hole exchanges yield

$$B: \sigma_{xy} \rightarrow 1 - \sigma_{xy} \quad (3b)$$

The transformations A and B together generate an automorphism group of $SL(2, \mathbb{Z})$. It would be desirable to have a dynamical understanding of the scaling properties in transitions between the plateaux, which seem to have universal values for their exponents. A useful dynamical guide [16] may be the self-dual spin model of Cardy and Rabinovici [17]:

$$Z(g^{-2}, \theta) = \text{Tr} \exp \left[-\frac{1}{2g^2} (\Delta_\mu \phi_a - 2\pi S_{\mu a})^2 + i p n_a \phi_a \right. \\ \left. + \frac{i p \theta}{32\pi^2} \epsilon_{\mu\nu} \epsilon_{\alpha\beta} (\Delta^\mu \phi^a - 2\pi S^{\mu\alpha}) (\Delta^\nu \phi^b - 2\pi S^{\nu\beta}) \right] \quad (4)$$

Here $\phi_{1,2}$ are dual lattice variables, the $S_{\mu a}$ are integer-valued plaquette variables, n_a is an external current, and the δ_μ are discrete derivatives. This model exhibits electric/magnetic duality:

$$S: z \rightarrow 1/z \quad (5a)$$

and the theta variable is periodic:

$$T: z \rightarrow z + 1 \quad (5b)$$

These transformations also generate [16] an automorphism group of $SL(2, \mathbb{Z})$:

$$Z_p(z) = Z_p(A(z)) : A \in \text{Aut}SL(2, \mathbb{Z}) \quad (6)$$

now for the full partition function, not just the plateaux (3). The notation (5) and the modular invariance (6) are familiar to adepts of string theory! The model (4) serves as an existence proof for the extension of complex duality ideas to the inter-plateau transitions, and motivates the application of string-like modular invariance (5) to deduce properties of critical points and

relations between exponents. Indeed, modular invariance gives good values for the longitudinal conductivity σ_{xx} [16]. This is a nice heuristic application of a top-down approach to a Condensed Matter problem using ideas obtained from string theory. To deduce the values of the critical exponents, a specific dynamical model with the complex duality property (6) is needed, and it seems [18] that a good candidate may be the $p \rightarrow 1$ -state limit of the Potts model, which corresponds to the percolation problem. This gives the index $\nu\beta = 7/3$, to be compared with the experimental value of 2.3 ± 0.1 , and percolation is reminiscent of the dynamical picture of the quantum Hall effect developed by Condensed Matter physicists. However, conformal field theory is not obviously applicable to the quantum Hall system, as we shall now see.

An interesting bottom-up approach to the quantum Hall effect starts from the observation that the electrons in a given Landau level form an incompressible fluid [19]. As such, one could expect the equations describing them to be invariant under diffeomorphisms preserving the phase-space volume, which constitute an infinite-dimensional symmetry. This has recently been demonstrated [20] in terms of the translation operators b, b^+ , in terms of which the operators

$$L_{n,m} \equiv (b^+)^n (b)^m + 1 \quad (7)$$

are defined, which obey the algebra

$$[L_{n,m}, L_{k,l}] = [(m+1)(k+1) - (n+1)(l+1)] L_{n+k, m+l} + \dots \quad (8)$$

This is a variant of an infinite-dimensional W_∞ -algebra, but, in the case of the integer planar Hall effect in which the level is completely filled, with a restriction of regularity at the origin and at infinity, which means that the generators can be represented in the form

$$L_{n+i, j} \equiv z^{n+i+1} \partial^{j+1} : \text{with the restriction } n, i > 0 \quad (9)$$

This algebra does not contain the full Virasoro algebra, so there is no reason as yet to expect that conformal field theory is applicable to the integer Hall effect. The algebra for the fractional Hall case in which the Landau level is only partially filled seems to be different, with more symmetry [20]. More W_∞ -algebra generators may also appear if one considers Hall conductors which are not entire planes, but have non-trivial topology (e.g., annuli), or are doped [21].

It will be interesting to see whether this microscopic bottom-up approach eventually makes contact with the previous heuristic top-down approach to the quantum Hall effect. It is also interesting to note that the first physicists

to study W_∞ -algebras were particle physicists [22], and that, as we will see later, W_∞ -algebras seem to play a key role in stringy black holes [23]. Thus this is another nice example of a connection between Condensed Matter Physics, Particle Physics and Quantum Gravity.

Another condensed matter problem about which particle theorists have been thinking is high- T_c superconductivity. As you know, this phenomenon occurs in materials such as La_2CuO_4 and YBa_2CuO_6 , which exhibit a gap Δ and the Meissner effect with magnetic flux quanta $1/2e$ [24]. They are believed not to be described by conventional BCS theory, because no strong isotope effect has been seen [25], as would have been expected for Cooper pairs bound by phonons (lattice vibrations), and the gap is surprisingly large [26]:

$$\frac{2\Delta}{T_c} \simeq 8 \quad (10)$$

to be compared with the value of 3.54 found in BCS superconductors. The important dynamics seems to be planar, and so it should be described by an effective 2+1-dimensional field theory. This has motivated the suggestion [27] that anyon condensation may be the mechanism for high- T_c superconductivity.

It is known that at low doping high- T_c superconductors are anti-ferromagnetic insulators [28], and they are believed to be described by a strongly-coupled Hubbard model [29], which is in turn described effectively by a 2-dimensional Heisenberg model [30]:

$$H = J \sum_{\langle ij \rangle} \underline{S}_i \cdot \underline{S}_j \quad (11)$$

At low temperature, this has the classical Néel ground state:

$$\underline{S}_i = S (-1)^{i_x + i_y} \underline{y} \quad (12)$$

with the direction of the vector $\underline{y}$ undetermined. The corresponding field theory is a 3-dimensional $O(3)$ sigma model with action

$$L_{O(3)} = \int d^3x (\partial_\mu \underline{u})(\partial^\mu \underline{u}) \quad (13)$$

which can be rewritten as a CP^1 model with $n = \bar{z}z : \bar{z}z = 1$ and action

$$L_{CP^1} = \int d^3x \left| (\partial_\mu - i S a_\mu) z \right|^2 \quad (14)$$

where S is a spin magnitude and a_μ is a non-dynamical "statistical" $U(1)$ gauge field. It is known that quantum corrections in the model (14) create in general a pole in the gauge propagator, whilst doping leads to holes that can be represented as fermions. Thus the effective action becomes that of QED₃:

$$L_{QED} = -\frac{1}{4} f_{\mu\nu} f^{\mu\nu} \quad (15)$$

The basic idea now is that in 2+1-dimensional systems it is possible to replace the usual London coupling

$$(\partial_\mu \phi - A_\mu)^2 \quad (16)$$

by one between the electromagnetic gauge field A_μ and the one-component statistical gauge field a_μ via the representation

$$\partial_\mu \phi = \mathcal{E}_{\mu\nu\rho} \partial^\nu a^\rho \quad (17)$$

This requires a mixed a/A Chern-Simons term

$$\frac{k}{4\pi} \mathcal{E}^{\mu\nu\rho} a_\mu \partial_\nu A_\rho \quad (18)$$

which is generated by fermions without any problem. However, there are other problems [31], due to the need for a Chern-Simons term for a_μ whose origin is unknown, the need for a mysterious cancellation mechanism to keep $m_a = 0$ at finite temperature, and the need to explain why P and T violation are not seen in the ground state.

One possible solution is that there are 2 Dirac fermions with opposite "statistical" $U(1)$ charges, as suggested by the consideration of microscopic models for holes in doped antiferromagnets [31]. This explains the absence of an induced Chern-Simons term for a_μ , but does give a mixed Chern-Simons term at the one-loop level, and yields a P - and T -invariant ground state. Moreover, it gives [32]

$$\frac{2\Delta}{T_c} \simeq 9 \quad (19)$$

as a first approximation, to be compared with about 8 for measured high- T_c superconductors and 3.54 for BCS theory. The difference can be traced to the fact that phonon-induced interactions are non-renormalizable, whilst the "statistical" (2+1)-dimensional gauge theory is super-renormalizable.

If this approach to high- T_c superconductivity is correct, it would be another nice example of the application to a Condensed Matter problem of ideas developed by particle physicists.

Let us now turn to symmetry breaking in the Standard Model of Particle Physics itself. It is well-known that the generation of particle masses requires the spontaneous breakdown of the $SU(2) \times U(1)$ gauge symmetry:

$$m_{W,Z} \neq 0 \Leftrightarrow \langle 0 | X_1, I_3 | 0 \rangle \neq 0 \quad (20)$$

with the nature of the unknown condensate X in equation (20) being one of the most important, and certainly one of the most pressing, problems in Particle Physics today. The observed ratio $\rho \equiv m_W^2/m_Z^2 \cos^2\theta_W \sim 1$ suggests that X mainly has $I = 1/2$, and this is also what is required to give masses to the fundamental fermions, both quarks and leptons.

Analogy with Condensed Matter Physics would suggest that the object X is composite, most likely a fermion-antifermion condensate $\langle 0 | \bar{F}F | 0 \rangle \neq 0$, like Cooper pairs in BCS theory or the quark-antiquark condensate $\langle 0 | \bar{q}q | 0 \rangle > 0$ in QCD. There are two favoured ideas of this type. One uses fermions of the Standard Model itself, in the form of a $t\bar{t}$ condensate [12], and the other postulates new fermions bound by new interactions, which goes by the generic name of Technicolour [13]. The alternative, and to my mind much more radical, possibility is that X is in fact an elementary Higgs field, as postulated in the original formulation of the Standard Model. I term this possibility more radical because no-one has ever found an "elementary" scalar field in Nature. The introduction of an elementary Higgs field would bring with it technical problems, in the form of quadratically-divergent loop diagrams that pose severe difficulties of naturalness, whose resolution presumably requires in turn the introduction of a new symmetry principle, namely supersymmetry, at an energy scale below about 1 TeV [33].

Precision data from LEP and elsewhere are for the first time giving us some significant constraints on the possible mechanism of electroweak symmetry breaking, and even some indications as to its nature. Figure 5 shows the constraints provided by the data in the (m_H, m_t) plane. At the $\Delta\chi^2 = 1$ level, we find [34]

$$m_t = 124^{+26}_{-28} \text{ GeV}, \quad m_H = 25^{+275}_{-19} \text{ GeV} \quad (21)$$

These are compatible with, and complement, the direct limits

$$m_t > 91 \text{ GeV (CDF)}, \quad m_H > 60 \text{ GeV (LEP)} \quad (22)$$

and spell trouble for some of the dynamical composite models that would require strong couplings and hence larger top quark and/or effective Higgs boson masses, as we now see.

The $t\bar{t}$ condensate model [12] normally requires a large $t\bar{t}$ -Higgs Yukawa coupling, corresponding to

$$m_t \simeq 200 \text{ to } 250 \text{ GeV} \quad (23)$$

and a bound-state Higgs boson weighing $(1 \text{ to } 2) \times m_t$. This region of the (m_H, m_t) plane is also shown in Fig. 5. It certainly looks to the naked eye as if this model is disfavoured, and one must in fact pay a price of $\Delta\chi^2 \simeq 8$ to live in this region [34]. This model could perhaps be rescued by adding epicycles in the form of additional parameters, but then it loses its elegance and simplicity, and becomes just the usual Standard Model written in terms of different variables.

In technicolour models [13], one postulates new fermions "technifermions" with new hyperstrong "techniQCD" interactions, which have a typical energy scale about 3000 times larger than LQCD and form bound states such as "technipions" with sizes about 3000 times smaller than that of the proton. The gauge bosons acquire masses by "eating" massless Goldstone bosons of the strongly-interacting techniQCD theory. One expects the physical spectrum to include a scalar state resembling the f_0 states of QCD, or the Higgs boson of the Standard Model, with a mass of order 1 TeV. In order to provide masses for the quarks and leptons as well as the gauge bosons, it is conventional to postulate a complete "technigeneration", each flavour of which comes in N_{TC} technicolours. In this case the physical spectrum will contain extra states, such as a plethora of pseudo-Goldstone bosons.

To compare with these technicolour models, it is useful to extend the above two-parameter (m_H, m_t) analysis to a 3-parameter space that is as model-independent as possible [35]. It can be expressed at the one-loop level largely in terms of vacuum polarizations. Several possible choices of variables to parametrize this space have been proposed, including in particular

$$\alpha S = 4s_W^2 \epsilon_3 = 4s_W^2 c_W^2 (\Delta\rho + \Delta r_W) + 4s_W^2 (c_W^2 - s_W^2) \Delta\kappa$$

$$\alpha T = \epsilon_1 = \Delta\rho \quad (24)$$

$$\alpha U = -4s_W^2 \epsilon_2 = -4s_W^2 c_W^2 \Delta\rho + 8s_W^4 \Delta\kappa - 4s_W^4 \Delta r_W$$

Figure 6 shows the $\Delta\chi^2 = 1$ ellipsoid in this space that is favoured by the precision electroweak data [34], together with the two-dimensional submanifold spanned by the Standard Model with $50 \text{ GeV} < m_H < 1 \text{ TeV}$ and $90 \text{ GeV} < m_t < 250 \text{ GeV}$. We see that the electroweak data indicate no need to go beyond the Standard Model region in this space. Figure 7 shows the projection [34] of the previous figure onto the $(\delta\epsilon_1, \delta\epsilon_3)$ or $(\delta T, \delta S)$ plane, together with the regions of this plane that are spanned in the Standard Model and various technicolour models with different numbers of technicolours, techniflavours and colours. We see that the technicolour models are clearly disfavoured, which is a reflection of the fact (21) that the data prefer a relatively light Higgs boson within the Standard Model, not a heavy, strongly-interacting one.

There are limitations to the precision with which this type of analysis can be carried out, since vertex diagrams, non-linear terms in the one-loop vacuum polarizations, and two-loop effects are not included fully. One must make some reference choice of (m_H, m_t) in order to fix values for the vertex and two-loop effects that cannot be ignored. The bounds on the contributions to (S, T, U) or $\epsilon_{1,2,3}$ depend on these reference values, and the position of the $\Delta\chi^2 = 1$ ellipse relative to the Standard Model region in the $\delta\epsilon_{1,3}$ plane depends on the reference values chosen [34], as seen in Fig. 8. However, this ambiguity is not enough to rescue technicolour models from experimental disfavour.

In the minimal supersymmetric extension of the Standard Model (MSSM), the lighter scalar Higgs boson is calculated [36] to have a mass around m_Z , which as we have seen above is favoured (21) by the electroweak data. Therefore, one could expect that the MSSM would itself be rather consistent with the data, and this is indeed the case [34], as we see in Fig. 9. Although the χ^2 of the MSSM fit does show some dependence on the MSSM parameters, this dependence is not yet sufficiently strong for any conclusions to be drawn about their probable values. However, Fig. 9 does indicate that the expected future improvements in the experimental precision could well start to constrain the MSSM model significantly, at least if m_t is also measured directly and is not too large.

The combination of the success of the supersymmetric GUT renormalization group predictions and the indications from LEP and other precision electroweak data on m_H provide two pieces of circumstantial

evidence for the supersymmetric worldview. But one smoking gluino or squark would be worth a thousand radiative corrections!

Let us turn finally to the question of symmetry and symmetry breaking in Gravity, which is an area where string theory should have a lot to contribute. Any list of the fundamental problems in Quantum Gravity must include those of setting up a finite or renormalizable perturbation expansion, quantizing around non-trivial classical solutions such as black holes and maintaining quantum coherence in the presence of event horizons, and the nature of singularities in space-time. It has recently been proven [37] that string perturbation theory in a flat space-time background is finite in every order, so string theory apparently resolves the first of these problems, thanks to conformal symmetry on the world-sheet and to modular invariance. Together with Nick Mavromatos and Dimitri Nanopoulos, I have been working on the problems of quantum coherence and singularities. We believe that we have made some progress in understanding the symmetries of string theory, their role in maintaining quantum coherence in scattering off black holes, how they are broken away from space-time singularities, and how the effective quantum mechanics obeyed by light particles may be modified by string corrections.

The suspicion that quantum coherence might not survive in the presence of objects with event horizons originated from the discovery of black hole thermodynamics [38], according to which a black hole has an unbounded statistical entropy:

$$S = A/4 = M^2 \quad (25)$$

and a related non-zero temperature:

$$T = 1/8\pi M \quad (26)$$

These findings suggested that an initially pure state might, through gravitational collapse, evolve into a mixed state, which is impossible in conventional quantum mechanics. The basic intuition behind this suspicion was the fact that information would be lost across any event horizon, necessitating a sum over all unobservable interior parts of the wave function, leading in general to a mixed state. This apparent problem arose initially at the macroscopic level, but it was subsequently suggested [39] that microscopic event horizons associated with topologically non-trivial space-time fluctuations - space-time foam - might force a modification of the fundamental laws of quantum mechanics and quantum field theory. Specifically, it was proposed that a density matrix formalism be adopted, and that the relation between in- and out-states might not be factorizable into the product of S-matrices, as usual:

$$\rho_{\text{out}} = \rho_{\text{in}} : \$ \neq S+S \quad (27)$$

If so, there would have to be a modification of the conventional quantum-mechanical Liouville equation for the evolution of the density matrix when averaged over time-scales much longer than the Planck time of 10^{-33} s [40]:

$$dp/dt = i[p, H] + dH/p \quad (28)$$

This equation is reminiscent of the familiar formalism for open systems [41], in which one chooses not to observe all the coupled degrees of freedom. However, the suggestion here is that the non-observation of some degrees of freedom is an intrinsic restriction, and not just a matter of choice or technological limitation.

Although this speculation all seems rather remote from experiment, it can perhaps be probed in the laboratory. Some of the best Particle Physics tests of quantum mechanics are those performed in the neutral kaon system. A few years ago, a phenomenological study of this system gave an upper bound on the magnitude of the matrix element of the dH term of about 10^{-21} GeV [38]. We were inspired by L. Maiani's talk on DAFNE during the phenomenological part of this meeting to reanalyze the bounds from existing neutral kaon data, and to discuss possible future measurements with the DAFNE e^+e^- accelerator. Unfortunately, we do not yet have a quantitative theory of the magnitude of such quantum-mechanics-violating interactions, although one might expect them to be suppressed by some power of (Λ_{QCD}/m_p) , as we now discuss.

Our recent studies in string theory indicate that there is no violation of quantum coherence in the presence of a single black hole [42]. This is because of an infinite-dimensional local space-time symmetry of the stringy black hole with the structure of a $W_{1+\infty}$ algebra [23], which links light particles to massive solitonic string states. The associated infinite set of conserved quantum numbers - W -hair - suffices to label all the black hole states, so that the statistical entropy (25) is only apparent, not real [43]. In principle, one can measure all the W -charges, and work with pure states at zero temperature [44]. As mentioned earlier in connection with Condensed Matter Physics, W -symmetry has a physical interpretation as the set of diffeomorphisms preserving a two-dimensional phase-space volume [45]. This gives us some intuition why the dH term in equation (26) should be absent in light-particle scattering off a single black hole: in its presence, as in an open system, the time-evolution would not be unitary and the phase-space volume element would not be preserved.

This does not mean that the dH term in (28) is absent in general. Indeed, we have recently argued [46] that it is necessarily present when one takes into account microscopic stringy black holes in the space-time foam. The above-mentioned W -symmetries couple light particle states to massive states, and hence the former must be treated as an open system whenever the latter are unobserved, as is the case in conventional laboratory experiments that are insensitive to massive solitonic string states. The latter

exert an apparent quantum-gravitational friction in the effective theory of light particles, which is therefore described by a modified quantum mechanics (28), even though the full string theory is in principle fully quantum-mechanical. One of the most sensitive microscopic tests of such a modification of quantum mechanics is in the neutral kaon system [40,47] that can be probed at DAFNE. A term of the form (28) could even cause the wave functions of macroscopic objects to collapse rapidly, so that they behave classically [46,48].

Let us now make some other comments on symmetries and symmetry breaking in stringy Quantum Gravity. String has been known for a long time to have an infinite set of local gauge symmetries [49], of which the best-known is general coordinate invariance associated with a spin-2 particle, the graviton. But there are other symmetries associated with higher-spin and other massive states, such as

$$k^\mu A_{\mu\nu\rho\sigma} - i B_{\nu\rho\sigma} = \sum_i k_{i\nu} G_{\rho\sigma} \quad (29)$$

The $W_{1+\infty}$ symmetry mentioned above is just a subset of these higher stringy symmetries. In general, they relate Green functions for particles of different mass, and hence may be spontaneously broken. At least one order parameter for this symmetry breaking is a non-singular value for the space-time metric:

$$\langle 0 | g_{\mu\nu} | 0 \rangle = \eta_{\mu\nu} \quad (30)$$

However, the above infinite-dimensional W -symmetry must survive any symmetry breaking. When the metric is singular, as at a space-time singularity, one would expect this symmetry to be enhanced by the absence of the order parameter (30). Indeed, we find an enhanced $W_{1+\infty} \otimes W_{1+\infty}$ symmetry at the singularity [50].

The spherically-symmetric stringy black hole is described by an $SL(2, \mathbb{R})/U(1)$ coset Wess-Zumino model on the world-sheet [42,51]. Near the space-time singularity, this becomes asymptotically a $U(1)$ topological gauge theory on the world-sheet:

$$S_{U(1)} = \int d^2x \, w \, \epsilon_{ij} \, \dot{r}^{ij} + \int d^2x \, Da Db \quad (31)$$

where a and b are $SL(2, \mathbb{R})$ parameters: $ab = 1 - uv$, where $u = e^w$, $v = e^{-w}$, and the spherical part of the metric is

$$ds^2 = du dv / (1 - uv) \quad (32)$$

From this we see that the singularity corresponds to $uv = 1$ and hence $ab = 0$. Conversely, if $\langle ab \rangle \neq 0$, as one could expect in a gauge theory, a non-singular space-time metric is generated. It is known that the $U(1)$ topological gauge field theory (31) can be written as a twisted $N=2$ super-Wess-Zumino coset model. This model has a super- $W_{1+\infty}$ symmetry, which contains a $W_{1+\infty} \oplus W_{1+\infty}$ bosonic subsymmetry. This enhanced symmetry at the space-time singularity is broken spontaneously by an infinite generalization of the Berezinsky-Kosterlitz-Thouless vortex mechanism [52] to the measurable $W_{1+\infty}$ that is responsible, in our interpretation [23], for the maintenance of quantum coherence in the presence of a stringy black hole. The breaking of the surplus W -symmetry is accompanied by an infinite set of (discrete) massless states, which provide the previously mysterious leg poles of the S -matrix for S -wave scattering off a spherically-symmetric stringy black hole. Moreover, the restoration of the double W -symmetry at the singularity explains [49] the triviality of the S -wave S -matrix at asymptotically high energies [53].

The appearance of W -algebras in such different areas as stringy black holes and the Quantum Hall Effect leads one to speculate that there might be a deeper connection between these diverse areas of Physics. Indeed, since the Torino meeting we have found that there is. Stringy black holes and other singularities have a natural description in terms of QED in three dimensions with complex fermions, similar to that of the Quantum Hall Effect [21,54]. The P - and T -violation of the associated vacuum correspond to the decay of black holes [55] and the cosmological arrow of time. Quantum Gravity and Condensed Matter Physics are even more closely related than we thought!

4 - SOME COMMON THEMES

I hope that the above idiosyncratic discussion has convinced you of the essential unity of physics, that the same theoretical techniques can be applied to many problems in Condensed Matter, Particle and Gravitational Physics, and hence that "phenomenologists" working in these different areas should talk to each other as well as to the "theorists" who develop useful field-theoretical tools for them. Among the particularly active common themes, I have picked out applications of the renormalization group and questions of symmetry and symmetry breaking. The latter is an especially "hot" topic in high- T_c superconductivity, the electroweak interactions, and now the stringy approach to Quantum Gravity.

A pervasive development is the study of lower-dimensional, often two-dimensional quantum field theory, either to describe extended objects such as strings, or to describe relevant dimensionally-reduced systems, such as high- T_c superconducting planes or spherically-symmetric black holes. The prototype of these lower-dimensional field theories has been conformal field theory in two dimensions, with manifold applications to Condensed Matter

Physics, possible relevance to the QCD strings that motivated particle physicists to introduce string theory in the first place, and now deep problems in Quantum Gravity.

Strings are the prototypes of extended objects, and have confronted theorists with a variety of infinite-dimensional symmetries, such as duality and modular invariance (cf strings and the quantum Hall effect), the Virasoro algebra (cf strings and critical phenomena), Kac-Moody algebras, and now W -algebras (cf the quantum Hall effect and black holes). The theoretical understanding of these infinite-dimensional algebras is as yet incomplete, indeed the Mathematics is often lacking, and the possible range of applications is only beginning to emerge.

If physicists are to develop and apply these and other tools expeditiously, we must maintain connections between theorists and phenomenologists and between the different subfields of Physics. As at this meeting, we must strive to talk to each other and at least understand each others' languages, even if we do not speak them fluently. Otherwise we will not be able to avoid in Physics the fate of the builders of that first Tower of Babel, that Sergio Fubini has warned us against in his article [1] for Luigi Radicati.

ACKNOWLEDGEMENTS

It is a pleasure to thank Sergio Fubini and Luis Alvarez-Gaumé for inviting me to this very interesting meeting, and for getting me to give this talk. It is a particular pleasure also to thank Nick Mavromatos for many discussions about the topics discussed here, and for encouraging me to write this talk. I also thank Peter Schmid for lending me the wherewithal to write the first draft, and Jeanne Rostant for polishing it into this final version.

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