Unified Theories

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Abstract
The present status of Unified Theories is summarized with special emphasis on their possible experimental tests. Outline: i) Unification of couplings; ii) Where can a positive signal come from? iii) HERA anomaly and Unification; iv) Recent progress in model building; v) Flavour and Unification.

1 Introduction and unification of couplings
In the description of the fundamental interactions among elementary particles, symmetries play a central role, more important than particles themselves. The diversity of particles and/or of their interactions can actually be often understood, in a way or another, as a manifestation of the underlying basic symmetries. As we know, three kinds of symmetries are or may be of relevance in these respects: space-time symmetries, intra-family (vertical) symmetries, inter-family (horizontal or flavour) symmetries. There is clear evidence for space-time symmetries, which might include supersymmetry, as there is compelling evidence for the vertical SU(3,2,1) gauge symmetry. On the contrary, the role and the nature of flavour symmetries is still controversial.

Unified theories can mostly be viewed as attempts to enlarge the role of these symmetries in the description of elementary particle physics. There is, in fact, circumstantial evidence in favour of an enlargement of the vertical SU(3,2,1) gauge symmetry to a more unified group, like SU(5) or bigger. Such evidence is both of algebraic and of empirical nature. The quantum numbers of the quarks and leptons of one generation fit into simple representations of the unified group, as observed more than twenty years ago [1]. Furthermore, the more recent precise measurements of the weak mixing angle $\sin^2 \theta_W$ and of the strong coupling constant $\alpha_s(M_Z)$ indicate their meeting with the electromagnetic coupling constant $\alpha(M_Z)$ at a large energy scale $M_G$ [2], provided the "low energy" spectrum includes the new particles implied by supersymmetry [3, 4]: to make a larger vertical symmetry working calls for an enlargement of the space-time symmetry, including supersymmetry, as also demanded by the need to stabilize the huge hierarchy between the weak and the unification scales.

This is illustrated in Fig. 1, which shows the prediction for $\alpha_s(M_Z)$ as function of an appropriately defined "mean" supersymmetric mass $T_{\text{susy}}$, ranging between 10 and 100 GeV in the "natural" region of parameter space. The band of the "SUSY GUT" prediction corresponds to what I think is a reasonable definition of the theoretical uncertainties associated with physics occurring at the high energy scale, like heavy thresholds [1] and/or Planck scale non renormalizable effects [2]. The agreement of such prediction with the current world average, $\alpha_s(M_Z) = 0.119 \pm 0.005$ [5], is remarkable. On the other hand, this figure makes clear that the unification of couplings does not set an upper bound on the scale of supersymmetric particle masses relevant to their foreseeable experimental search. On the contrary, it determines with significant precision the value of the unification scale.

Fig. 1 also shows the central value of the "string theory prediction", defined by requiring, with the same spectrum as in the "SUSY GUT" case, the meeting of the three couplings at the string scale $M_{st} = 4 \times 10^{17}$ GeV [6] with an arbitrary Kac Moody coefficient for the hypercharge U(1) factor. The discrepancy between $M_{st}$ and $M_G$, as determined by Fig. 1 itself, is the source of the problem. By no means, however, this must be viewed as a conflict between field theory and string theory. String theory, which actually forces unification of the gauge couplings also with the gravitational coupling, can still require $\alpha_s(M_Z)$ to be in agreement with the observed value in several ways. At least three such ways have been put forward: i) a stage of Grand Unification, in the usual field theory sense, below the string scale [6] [2]; ii) a modification of space-time below the GUT scale

\footnote{Not displayed in Fig. 1 is a low energy threshold effect due to light superpartners which may, but need not, increase the prediction for $\alpha_s(M_Z)$ by about 5% [6]}

\footnote{Provided the spectrum below $M_G$ is the one of the Minimal Supersymmetric Standard Model}
which influences the energy dependence of the gravitational constant but not of the gauge couplings \[12\]; iii) the addition of extra matter multiplets at intermediate energies or close to the GUT scale \[13\]. In particular only i) requires an intermediate stage of field-theoretical Grand Unification, which, therefore, may or may not be necessary. For model building it is important to have a view on the relative plausibility of these two alternatives. Of help, to this purpose, it would be to know better which are the consequences, at the large scale, of the non-GUT picture, as derived from string theory. Can we distinguish the two alternatives in a phenomenological way other than discussing the unification of couplings itself? Hereafter, when important, by Unification I will mean Grand Unification.

2 Where can a positive signal come from?

It is both logical and useful, at this stage, to briefly recall the ways to find an experimental signal of supersymmetry and Unification. They are summarized in Table 1, together with a qualification of their significance. All boxes of this Table require, as always, an element of judgement. Let me briefly comment on each of them, not before having noticed that an entry on neutrino masses might have been added to the list. Neutrino masses are indeed generally expected in a Unified Theory. The reason for not having such an entry in Table 1 is twofold: neutrino masses are not a specific prediction of Unified Theories only, nor there is a value for neutrino masses that Unified Theories clearly prefer, at least in my view. Having said that, I will have to defend the insertion of "Non Standard FCNC" in Table 1. The last part of the talk is devoted to this issue.

Although somewhat model dependent, "naturalness" bounds hold on the supersymmetric particle masses, requiring some of them to be below 1 TeV and, in some cases, well below that limit \[14\]. The relationship between the Z-mass, or the Fermi scale, and the masses of the superpartners allows to define a "natural" region of the parameter space. In supergravity models, the exploration of 90% of this region (or allowing up to a 10% fine-tuning among the various parameters) gives upper limits on the masses of the gluino, the lightest stop, the lightest chargino and the lightest neutralino of about 350, 300, 90, 50 GeV respectively. This region is therefore being significantly explored by present (so far negative) searches \[15\]. In general, these limits scale as the square-root of the ratio of the allowed amount of fine tuning. As such, even a 99% probability bound still requires all these particles to be lighter than about 1 TeV. Bounds weaker by about one order of magnitude apply to the sfermions of the first two generations, because of their small Yukawa couplings to the Higgs \[16\].

As discussed later on, "gauge-mediation" models \[17, 18\] are considered as alternative to "supergravity" models \[19\] in the description of supersymmetry breaking. Since the spectrum of superpartners changes in the
two cases, so do the naturalness bounds, as illustrated in Fig. 2, taken from Ref. 20 (See also Ref. 21). There the bounds (p > 90% or p > 99%) are compared in the two cases for the lightest neutralino and for the right-handed stau, taking into account the correlation in the respective parameter spaces. All this substantiates the statement that finding superpartners below 1 TeV is a necessity in Unified Theories. Conversely, discovering superpartners in this energy range would prove supersymmetry as a relevant symmetry in nature but would still only be an indirect sign of Unification, unless detailed measurements of the superpartner spectrum are made.

The detection of proton decay appears as second entry in Table 1, in fact under the column "Sufficient". Unfortunately, this search cannot be also qualified as "Necessary". The only firm prediction of supersymmetric Unification is the rate for the $e^+\pi^0$ mode, mediated by vector boson exchanges,

$$\tau(p \to e^+\pi^0) = 1 \cdot 10^{35\pm1}(M_G/10^{16} GeV)^4 \text{years}$$  \hspace{1cm} (1)$$

to be compared with the present limit on this mode of $6 \cdot 10^{32}$ years 22 and with the expected sensitivity of the Superkamiokande detector, after 10 years of running, of about $10^{33}$ years. More favourable modes could be $p \to K^+\nu_\mu$, $p \to K^0\mu^+$, $n \to K^0\nu_\mu$, since they might occur at higher, but also more uncertain rates than (1) 23, 24.

Several detectors are active in the world searching for dark matter in our galaxy in the form of Weakly Interacting Massive Particles. A positive signal would be a significant indication in favour of supergravity type models. In a relevant portion of their natural parameter space, these models require the lightest neutralino to be a cold dark matter particle, as the relic abundance of neutralinos from the big bang can be safely calculated 25, 26. Within an uncertainty factor of about 5, it is also possible to estimate the expected event rate, per kg, per day, in a given WIMP dark matter detector. Current detectors are not yet capable to compete significantly with direct searches of supersymmetric particles, except in some corners of parameter space 26. They will, however, when sensitivities considered achievable with present technology (e.g. 0.01 events/kg/day in a Ge or in a NaI detector) are reached.

The discovery of a light Higgs should also be viewed as a very strong indication in favour of supersymmetry and, indirectly, of supersymmetric Unification, even without knowing if its properties deviate from those expected for the Standard Model Higgs. Supersymmetry predicts a full set of Higgs particles, among which one at least should be relatively light: less than about 120 − 130 GeV 27 in the model with minimal low energy particle content and than about 150 − 160 GeV 28 in a generic model.

Finally the last entry in Table 1 is discussed with special attention below.

3 HERA anomaly and Unification

An anomaly of the high-$Q^2$ events in $e^+p$ scattering has been presented at this Conference 29 and it has been discussed as a possible evidence for new physics 29, 30. Such an anomaly could be due, although in any case not without difficulties, to some new contact interaction or to the production of an s-channel resonance 30. Since Unification is a leading candidate for extending the Standard Model, it is natural to ask if and how this anomaly, supposedly confirmed by further necessary data, could be described in a Unified picture.

Two different contact interactions, or a combination thereof, invariant under $SU(3,2,1)$, might perhaps be responsible of the HERA-anomaly and not be in conflict with any other experiment so far. They are composed by the following two chains of 4-fermion interactions 30, 31 ($L$ and $Q$ are lepton and quark doublets, of given

| Find | Sufficient | Strong Indication | Necessary |
|------|------------|-------------------|-----------|
| Superpartners below 1 TeV | √ | | √ |
| Proton decay | √ | | |
| WIMP Dark Matter | | | √ |
| A light Higgs | | √ | |
| Non Standard FCNC | | | |

Table 1: Summary of possible signals for supersymmetry and Unification.
chirality)

\[ L_L \gamma_\mu L Q_R \gamma_\mu Q_R + L_R \gamma_\mu L R Q_L \gamma_\mu Q_L, \]
\[ L_R \gamma_\mu L R (Q_L \gamma_\mu Q_L - Q_R \gamma_\mu Q_R), \]

weighted by an appropriate inverse squared energy scale. In short, I do not know how to make these effective interactions emerge from any sort of Unified Theory with decent assumptions about the dynamics or the symmetry breaking pattern. The need to sufficiently suppress any other similar interaction not seen in other experiments or in HERA itself is the major difficulty.

At least in principle, it is easier to accommodate in a Unified Theory a new particle being exchanged in the s-channel, in particular a scalar leptoquark, as the origin of the HERA-anomaly. To make the game less wild, let me consider the possibility that this leptoquark is actually a s-quark with a superpotential coupling of the form

\[ \lambda'_{113} L_1 D_1 Q_3, \]

where \( L_1, D_1, Q_3 \) are the left-handed lepton doublet of the first generation, the down-type quark singlet of the first generation and the third generation quark doublet respectively. The scalar top in \( Q_3 \), with a mass of about 200 GeV, would be the leptoquark supposedly produced at HERA with a coupling \( \lambda'_{113} \) at the few percent level.

Even this interpretation is not without "potential" difficulties, however. One is generic: the presence of other \( \lambda' \) couplings, similar in strength to \( \lambda'_{113} \) but with different flavour indices, would induce unobserved FCNC interactions. Another difficulty is more tied to the very concept of unification: why not to have, together with (4), also the couplings (\( E \) is the charged lepton singlet and \( U \) the up-type quark singlet)

\[ \lambda_{ijk} L_i L_j E_k + \lambda''_{ijk} D_i D_j U_k, \]

as a genuine full "vertical" symmetry would suggest? I have called these difficulties "potential" because it is possible to set initial conditions on fully unified couplings, for example \( SU(5) \)-invariant ones, which at low energy, consistently with renormalization rescalings, avoid these problems. If more data were to confirm the anomaly and strengthen its leptoquark interpretation, it would become interesting to see if and how these initial conditions could be made natural in some sense.

\[ ^3 \text{The right-handed-neutrino in } L_R \text{ is there only for simplicity of notation.} \]
4 Recent progress in model building

In model building of Unified Theories, two main problems remain open, at least in the sense that no possible solution clearly emerges yet over the others:

i) The supersymmetry breaking problem. One has to originate the soft supersymmetry breaking parameters in the scalar potential as well as the so called "µ-term". All these parameters are characterized by a scale $\Lambda_{SB}$, defined as the scale at which the corresponding Lagrangian terms cease to appear as local interactions.

ii) The flavour symmetry breaking problem. Here the relevant parameters are the Yukawa couplings, also depending on a scale $\Lambda_{FB}$, defined in an analogous way to $\Lambda_{SB}$.

Both these problems are not particularly new. Some new inputs, however, have influenced the recent developments in this area. One is a technical tool: the dynamics of strongly coupled supersymmetric field theories is better understood, mostly due to the work of Seiberg and Seiberg and Witten [35], further developing earlier work in the eighties [36]. The second input is due to a better focus on the connection that actually exists between the two problems mentioned above. Such connection makes it useful to divide the possible theories in two classes, depending on the relation among $\Lambda_{FB}$, $\Lambda_{SB}$ and $M_G$:

1) "supergravity-type" theories, characterized by $\Lambda_{SB} \geq \min(\Lambda_{FB}, M_G)$;
2) "gauge-mediation-type" theories, for which $\Lambda_{SB} \ll \min(\Lambda_{FB}, M_G)$.

From a general point of view, the important difference between these two classes of theories is that in the first case, unlike the second one, the supersymmetry breaking parameters necessarily feel also the breaking of flavour, at least as an effect of radiative corrections. Such coupling was pointed out long time ago already in the context of the Minimal Supersymmetric Standard Model [37] and later realized to be even more important in the GUT case [38], especially because of the heaviness of the top quark [39].

As a result of these new inputs, special efforts have been made in studying explicit renormalizable field theory models of dynamical supersymmetry breaking. This is relevant in the case of "gauge-mediation-type" theories, since there, by definition, $\Lambda_{SB}$ is lower than $M_G$, a scale at which renormalizable field theory should already be effective. As a result, using strongly coupled theories, several mechanisms for dynamical supersymmetry breaking have been designed, too many to be described in detail. The following might at least be a not too incomplete list:

1. Strong coupling models [36];
2. Dynamically generated superpotentials [40];
3. Confinement without chiral symmetry breaking [41];
4. Quantum modified constraints [42];
5. Product groups [43];
6. Plateau of supersymmetry breaking false vacua [44].

Are these mechanisms any useful? I think they are, since they make possible the construction of complete and relatively simple realistic examples of Unified Theories based on gauge-mediation, putting them on essentially equal footing than models based on supersymmetry breaking transmitted by supergravity couplings. Some further progress in this direction might still occur.

Is it then a "supergravity-type" or a "gauge-mediation-type" theory which is realized in nature, if any? Experiments can and must decide, on the basis of the following phenomenological differences:

i) Different spectra of the superpartners, with, e.g, s-quarks and s-leptons significantly more separated in mass in the "gauge-mediation" case [45].

i) Different behaviour of the "Lightest Supersymmetric Particle". In "gauge-mediation" the LSP is always the gravitino, to which the lightest among the usual superpartners, most likely a neutralino or a stau, decays. The wide variety of possible lifetimes, consequence of a largely unconstrained gravitino mass, may lead, in turn, to very different experimental signatures: prompt $2 \gamma$'s, delayed $\gamma$'s, heavy charged tracks, etc.

iii) Different flavour physics. Although this is not a theorem, I am convinced that any sensible Unified Theory based on supergravity will significantly deviate from the SM expectations in some flavour physics observable [39], whereas this need not be the case in gauge-mediation models.

This brings me to the last subject of this talk, on which I wish to expand my comments a bit.
5 Flavour and Unification

Supersymmetry, as most extensions of the SM, introduces new sources of FCNC and/or of CP violation. In general, this simply happens because of the extended particle spectrum, which allows new flavour changing and/or CP violating interactions to be written down.

Some of these new interactions are still controlled by the same Cabibbo Kobayashi Maskawa matrix, $V_{CKM}$, which appears in the standard charged current weak interactions. The related new effects are there no matter how supersymmetry is broken and are therefore present in any realistic supersymmetric extension of the SM. Observables that could be affected in a significant way by these new sources of flavour violations, depending on the spectrum of the superpartners, are the inclusive $b \to s(d) + \gamma$ [10] and $b \to s(d) + t^+t^-$ [11] rates. The current experimental average branching ratio for $b \to s + \gamma$, $(2.55 \pm 0.61) \times 10^{-4}$ [12], compared with the pure SM prediction, $(3.48 \pm 0.31) \times 10^{-4}$ [13], still leaves room for a sizeable new contribution, negatively interfering with the SM amplitude.

In general, however, other sources of FCNC/CP-violations are present, not controlled by the CKM matrix. A necessary condition for their physical relevance is the non degeneracy, in flavour space, of the supersymmetry breaking masses of the scalar partners of fermions with given charge and chirality. If supersymmetry and flavour breaking are decoupled, as in "gauge-mediation-type" models, no such extra source of FCNC/CP-violation needs to be present. In the opposite case, like in "supergravity-type" models, they are present [14] and expected to be sizeable if Grand Unification is realized [15, 16]. In general these effects are described by new unitary mixing matrices occurring in the gaugino vertices, called $W$ hereafter, and by some other FCNC/CP-violating parameters in the analytic scalar potential. Generically, these models are actually in serious danger of conflicting with existing observations, or non observations, due to supersymmetric FCNC/CP-violating loop effects [17].

For this reason, several ideas have been recently put forward to avoid this problem, referred to as the "supersymmetric flavour problem". An attempt to summarize them is made in Table 2, also including the "Universality" option. Given the variety of possibilities, there is a significant amount of arbitrariness in preparing this Table. To balance this arbitrariness, it will be useful to consider the original references and also the discussion given by Nir [18] at this Conference on related matters.

I have already commented upon the "Universality" case [19], which can certainly be realized in "gauge-mediation-type" models [20]. It is possible to get close enough to it even in supergravity, with universal boundary conditions, if no Unification is realized, since the flavour-breaking renormalization effects due to the top Yukawa couplings, $\lambda_t$, [21] are small enough and, most importantly, they do not introduce new CP-violating phases nor they affect leptons. Maybe a dynamical way of realizing "Universality" in supergravity exists, using strong renormalization effects which could lead the supersymmetry breaking masses to flavour-universal fixed points [22]. However, I have not yet seen nor have been able to find myself a fully realistic realization of this idea.

The ideas that try to solve the "supersymmetric flavour problem" without resorting to flavour-degenerate scalar masses can perhaps be grouped into three distinct categories: i) Alignment; ii) Heavy $\tilde{f}_{1,2}$; iii) Non Abelian Flavour Symmetries.

In its simplest version, Alignment [23] is the notion that some Abelian flavour symmetry may force the Yukawa coupling matrix responsible for the down-type quark to be (approximately) diagonal with the down s-quark mass matrices in the same superfield basis. This is as saying that the neutral gaugino interactions of the down quark-squarks will not involve any non trivial $W$-mixing matrix, thus keeping under control an otherwise
very problematic effect in $\Delta S = 2$ transitions, especially related to the $\epsilon$ parameter in kaon physics. One should not forget here that another very stringent constraint on FCNC/CP effects comes from the non-observation, so far, of any Lepton Flavour Violating process like $\mu \rightarrow e + \gamma$. To satisfy this new constraint requires an alignment in the lepton sector too. Although this is possible, I do not know how to make all this consistent with Unification. The most likely signatures of Alignment are in any case related to the mixing matrices $W$ in the up quark-squark sector, i.e. occurring in the neutron Electric Dipole Moment, via the u-quark EDM, and in mixing or CP-violation in the charm system.

The fact that the most dangerous FCNC/CP effects come from exchanges of non-degenerate scalars of the first and second generations can be put together, in an attempt to alleviate the problem, with the observation, mentioned in Sect.1, that these same scalars can be considerably heavier than those ones of the third generation, between 1 and 10 TeV, without conflicting with the naturalness constraint. This possibility is called “Heavy $f_{1,2}$” in Table 2. Although this is enough to suppress the LFV processes, this is not the case for the $\epsilon$ parameter, which requires a further suppression by about two orders of magnitude, maybe coming from the smallness of the relevant phase(s).

Finally, it is not possible that the same flavour symmetry that keeps the CKM matrix and the $W$-matrices close to $1$, also forces the first and second generation scalars to be degenerate enough to solve the $\epsilon$ and the $\mu \rightarrow e + \gamma$ problems automatically? Among many different alternatives, a clear candidate emerges for such a symmetry, which is consistent with Unification: a $U(2)$ symmetry acting on the three generations of matter fields $\Psi_i, i = 1, 2, 3$, as a doublet plus a singlet,

$$\Psi_i = \Psi_\alpha + \Psi_3, \alpha = 1, 2,$$

and trivially on the Higgs fields. Whereas $U(3)$ is the largest flavour symmetry group in presence of full vertical Unification and for vanishing Yukawa couplings, $U(2)$ is the leftover subgroup after taking into account the large $\lambda_i$. The key observation is that, in the limit of unbroken $U(2)$, the first two generations of fermions are massless, $m_{f_1} = m_{f_2} = 0$, the first two generations of sfermions are degenerate, $\tilde{m}_{f_1} = \tilde{m}_{f_2}$ and the CKM-matrix is $1$, as are the $W$-matrices. Therefore, a simple pattern of small $U(2)$-breaking can correlate the small fermion masses $m_{f_1}$ and $m_{f_2}$ to slightly non-degenerate sfermions of the first two generations, $\tilde{m}_{f_1} \neq \tilde{m}_{f_2}$, and to small deviations from unity of both $\nu_{CKM}$ and the $W$-matrices.

The interesting outcome of all this, other than the correlation between fermion masses and the CKM parameters, is that the significant FCNC/CP effects from supersymmetric loops come from the third generation of sfermions not being degenerate with the first two and with $W$-mixing angles similar to the corresponding CKM angles. In turn, this gives effects of naturally similar magnitude as the SM effects both in $\epsilon$ and in $B - \bar{B}$ mixing, which all come from top exchanges. This is consistent with present observations. It should no longer be, however, after the experiments foreseen in B-physics in the next few years, if the new phase in the relevant $W$-matrix is of order unity.

6 Conclusions

The theoretical case for Unified Theories is strong and supported by a piece of empirical evidence, the successful prediction of the strong coupling constant.

Means exist to establish or strongly indicate supersymmetric Unification experimentally, some of which are compelling: the searches for supersymmetric particles and for a light Higgs, both within reach of facilities now active or under construction. Motivated by supersymmetry and Unification are also the searches for proton decay and for dark matter in the form of WIMPs.

Finally, several observables in flavour physics are likely to be affected in a significant way by virtual exchanges of supersymmetric particles. This will have to be the case, I believe, if Unification is realized in the supergravity way, with flavour breaking coupled to supersymmetry breaking. In some cases, like the $\epsilon$ parameter and mixing or CP violation in the B-system, the supersymmetric effects compete with the SM effects, from which they have to be disentangled. In other cases, like in $\mu \rightarrow e + \gamma$ and in the electron and neutron EDMs, these effects stand as unambiguous signals of new physics. Their finding, together with the study of the CKM parameters, might
also shed light on the role, so far elusive, of flavour symmetries. I consider the experimental effort in these
directions very worthful.

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