

Scientific highlights

a) The origin of mass

(Palaiseau, Saclay, Greece, INFN, Trieste, Lisbon, Madrid, Valencia, Oxford, CERN)

A high-precision scheme was proposed, Supersymmetry Parameter Analysis (SPA), and provided a repository for computer programs relating the Lagrangian parameters to physical observables at LHC and e^+e^- linear colliders, i.e. masses, mixings, decay widths and production cross sections for sparticles. A new model for fermion masses was proposed that provides an excellent fit to all the experimental data, in terms of very few parameters. A systematic study of discrete symmetries has been performed as the origin of the observed mixing in the lepton sector. Building on the realisation that bi-tri-maximal mixing in the lepton sector can naturally be obtained in discrete non-Abelian models, considerable progress has been made in constructing fully realistic models of fermion masses and mixings. Their possible string theory origin has also been studied.

An update of the Unitarity Triangle analysis was performed, using the recent experimental results in B_d , B_s physics. The generalization to several new physics scenarios was used to strongly constrain the scale of new physics, with profound implications for model building. New methods to investigate the CKM matrix using three-body B decays were proposed. NLO QCD corrections to the electric dipole moment of the neutron were computed, and their phenomenological impact was assessed. Progress was made in the computation of electric dipole moments in the case of supersymmetry with heavy scalars (Split Susy). The predicted results are within the sensitivity of forthcoming experiments. Lepton number violation and the ‘little fine-tuning’ problem have been studied. The complementarity between lepton flavour violation and LHC experiments has been analysed to probe supersymmetric grand unified theories.

In neutrino phenomenology detectability of high energy neutrinos was studied. This includes accelerator neutrinos in the long base-line experiments, cosmic and atmospheric neutrinos. Models for neutrino masses and mixings were proposed and confronted with the experimental data. A mechanism of screening of the Dirac structure in the seesaw mechanism and lepton mixing has been proposed. It allows to reconcile the quark-lepton unification and strong difference of the quark and lepton mixing patterns. As an alternative possibility, an approach based on the universal mixing matrices of quarks and leptons was developed. The most general seesaw equation for neutrino masses in left-right symmetric models into the right-handed neutrino spectrum was resolved and the constraints from leptogenesis on the eightfold solutions were extracted. Neutrino masses and mixing were also studied within the MSSM supplemented by a $U(1)$ anomalous family symmetry and additional Higgs singlets. A lepton number violating dimension-five operator was used to derive the general form of the charged lepton and neutrino mass matrices. The coherent contribution of neutrons in neutrino-nucleus scattering due to the neutral currents was suggested to help in detecting supernova neutrinos. A world wide network of such detectors was proposed. It could also be used to study low energy neutrino oscillations and non-standard properties of neutrinos.

b) Supersymmetric phenomenology

(Bonn, INFN, Trieste, Lisbon, Madrid, Valencia, Oxford, Warsaw, CERN, US team)

The problem of mass scales in supersymmetric models has been investigated. The concept of improved naturalness was introduced. The idea is to construct theories that are

more natural than the standard model, in the sense that they are valid to a larger natural cutoff scale, while at the same time preserving consistency with the electroweak precision tests. A simple origin for dark matter in such theories was explored. Theories studied include twin Higgs models, 2 Higgs doublet theories with a light Higgs, and two Higgs doublet models with one inert having no expectation value and no coupling to fermions. Predictions are given for multilepton events with missing transverse energy at LHC, and for the direct detection of dark matter. Furthermore, it was proposed that the Higgs boson mass in supersymmetry may be not as light as generally thought, consistently with all known constraints and with striking predictions at LHC. This arises in the two Higgs doublet model with heavy Higgs and top quark interactions that approach strong coupling.

Based on considerations of naturalness and electroweak precision tests, a new framework for supersymmetric model-building, lambda-SUSY, was introduced and analyzed. Natural explanation of the fact that the supersymmetry breaking scale is bigger than the electroweak symmetry breaking scale was proposed within models with extended electroweak gauge groups. Supersymmetry and global symmetries were used to stabilize the Higgs mass for the gauge groups $SU(2)_L \times SU(2)_R \times U(1)$ and $SU(3)_W \times U(1)$. A detailed study of the Higgs sector in models that go beyond the minimal supersymmetric standard model was performed. Models with spontaneous R-parity breaking were studied in detail.

A new viewpoint, based on the statistics of vacua, on the issue of fine-tuning in supersymmetry was proposed. Its most likely expectation is that a 1-loop hierarchy between the Z-boson mass and the the sparticle masses exists, thus explaining why sparticles are elusive at LEP and also why they should be found at the LHC. It was also pointed out that, given the LEP bounds on sparticle masses, the most favourable situation to obtain a realistic Dark Matter candidate within supersymmetry is for the lightest supersymmetric particle to be a “well tempered” combination of bino with chargino or higgsino. This also implies the generic presence of almost degenerate neutralinos at the LHC.

A new anomaly mediated model with all mass scales generated dynamically was constructed which avoids the tachyonic slepton problem. The susy spectrum and the implications for Higgs searches has been explored. New constraints on SUSY flavour mixing have been obtained with important implications for LHC. The impact of the measurement of Bs-Bsbar mixing on SUSY sources of flavour violation was assessed. The calculation of gluino contributions to FCNC at the Next-to-Leading order was completed, while the corresponding phenomenological analysis is under way. Models with ‘Split extended Supersymmetry’ were also analysed, as well as SUSY models with multiple Higgses. Finally, the present experimental limits on electric dipole moments were used to bound the new physics thresholds where CP is maximally violated within the Supersymmetric Standard Model. The resulting bound on their scale is surprisingly strong, around 10^7 GeV.

The neutrino role in SUSY GUTs in the determination of fermion masses and mixings in $SO(10)$ models has been investigated. Minimal realistic GUT models, based on $SU(5)$ and $SO(10)$ gauge symmetry groups, have been explored. The Yukawa sector of non-SUSY $SO(10)$ model was studied as well as the CP violation in minimal renormalizable SUSY $SO(10)$. Constraints from proton decay were obtained for supersymmetric $SU(5)$ and flipped $SU(5)$. The influence of large mass lightest Higgses has also been studied. Motivated by string theory constructions, the possibility to uplift a (supersymmetric) AdS vacuum to a positive cosmological constant was studied, using interactions of the matter in the hidden sector, and the resulting supersymmetry breaking patterns were analyzed.

c) Particle astrophysics and cosmology

(Palaiseau, Saclay, Greece, INFN, Trieste, Lisbon, Madrid, Valencia, Oxford, Warsaw, CERN)

Important effort has been dedicated to the study of supersymmetric candidates for dark matter (DM) and their possible detection. Programs for calculating high-precision low energy observables, the density of cold dark matter (CDM) in the universe, as well as the cross sections for CDM search experiments were introduced. The effect of a strong coupling between DM and dark energy was investigated on the rates for the direct detection of DM. It turns out that the average and maximum WIMP energy increases, which allows the possibility of designing experiments measuring gamma rays following nuclear de-excitation. Density profiles and velocity distributions of the lightest sparticle (LSP) in our vicinity were analyzed, while the spin contribution to the LSP-nucleon scattering cross section was extracted. The 1-loop computation of the neutralino-neutralino annihilation to gamma Z has been performed. Constraints on the possible existence of a new gauge boson and light DM have been analyzed. The effects of extra dimensions on supersymmetric DM components were studied with the computer code Dark Susy.

The cosmological evolution of the universe was studied when the quintessence solution to the dark energy puzzle is modeled within supergravity, broken in a hidden sector, with observable matter in a third sector. The dependence of fermion masses on the quintessence field was computed. Much effort has been also dedicated to the study of lepto/baryogenesis and connection to leptonic CP violation. It was shown that flavour effects are crucial in determining the baryon asymmetry within the leptogenesis scenario, and that CP violation in the leptonic sector is connected to the baryon asymmetry. Approximate analytic results were derived, showing that the commonly used expressions for the lepton asymmetry, which depend on the total CP asymmetry and one single efficiency factor, may fail to reproduce the correct result in a number of cases. Possible connections between low-energy neutrino physics, CP-violation and the cosmological baryon asymmetry of the Universe were also explored. The maximal CP asymmetry in scalar triplet leptogenesis has been determined.

The cosmological manifestations of neutrinos and other light particles were analyzed in view of the results of the WMAP experiment. The possibility of constraining the expansion rate of the universe well before nucleosynthesis, using measurements of the flux of cosmic antiprotons, was analyzed. A study of neutrinos coming from supernovae has been completed and shown that their observation can detect sterile neutrino components more sensitively than earth based experiments and also give detailed information on the shock wave passing through the supernovae. Flavor conversion due to neutrino-neutrino interactions has been studied in the context of supernovae and early universe. The possibility that cosmological density perturbations are generated by the inhomogeneous decay of right-handed neutrinos was studied. Robust predictions of the model are a detectable level of non-Gaussianity and, if standard leptogenesis is the source of the baryon asymmetry, a baryon isocurvature perturbations at the level of the present experimental constraints. Possible modifications of axion scenarios which are compatible with recent astrophysical observations have been introduced.

Issues related to the non-Gaussianity in CMB anisotropies were studied. The full system of Boltzmann equations at second-order describing the evolution of the photon, baryon and CDM fluids was obtained. These equations allow to follow the time evolution of the Cosmic Microwave Background (CMB) anisotropies at second-order at all angular

scales from the early epoch, when the cosmological perturbations were generated, to the present through the recombination era. Further progress has been made in the calculation of non-gaussianity in inflation and shown to be large in a class of Curvaton models, such as supersymmetric Peccei-Quinn models with the curvaton corresponding to an angular degree of freedom orthogonal to the axion. The mechanism can accommodate low-scale inflation with Hubble parameter at the TeV scale such as modular inflation.

Inflationary models have also been studied extensively. Simple inflationary potentials in supergravity theories with no-scale Kähler potentials and moduli stabilization were investigated. Fine tuning necessary for the slow roll inflation was discussed for D-type and F-type stabilization. The results were compared to the recent WMAP3 data. The inflation in racetrack models from Wilson lines coming from the string has been shown to be viable and a possible origin of the initial conditions for inflation was identified. The possibility of forming sub-horizon black holes at the end of inflation has been studied. Progress was made towards the understanding of the initial conditions of the universe. A framework was proposed that combines the string landscape with no boundary initial conditions. In this framework, amplitudes for alternative histories for the universe are calculated with final boundary conditions only. This leads to a top down approach to cosmology, in which the histories of the universe depend on the precise question asked. Focussing on a simple model, it was shown that predictions on inflation can be made.

The production of gamma rays from ultrahigh energy cosmic rays has been studied. Both theoretical approaches and numerical tools were developed to address questions involving propagation of cosmic rays, gamma rays and neutrinos. The production of gravitational waves from phase transitions in neutron stars has been considered. The cosmological phase transition between the AdS-Schwarzschild phase (hot CFT phase) and the phase with RS1 geometry was further studied in the RS1 model. It was argued that gravitational waves, detectable at LISA, should provide a signal of this phase transition. A frame-invariant formulation of scalar-tensor theories was developed, which can be useful to exploit the positive and complementary aspects of Einstein and Jordan frames. Renormalization group techniques were applied to improve Eulerian perturbation theory computations on the growth of cosmic large scale structures. The conditions to violate the null energy condition (NEC) were studied within an effective field theory approach. It was proven that NEC violation without instabilities, *i.e.* without ghosts or tachyons, implies both the presence of superluminal modes and the breakdown of isotropy.

d) String phenomenology

(Palaiseau, Bonn, Greece, INFN, Trieste, Madrid, Oxford, CERN, US team)

Several research directions which explore the experimental consequences of string theory vacua were explored. Progress has been obtained in the study of the effects of fluxes on string compactifications. In particular the study of generalized fluxes in Type IIA and Type IIB toroidal orientifold compactifications and an analysis of up-lifting terms in the KKLT scenario. Moduli stabilization in certain IIA vacua with fluxes was obtained and effects of oblique internal magnetic fields in type I superstrings compactified on tori and orbifolds were studied. M-theory compactifications on manifolds with G_2 holonomy or with $SU(3)$ structure were studied. Explicit examples with all moduli fixed which preserve $N = 2$ or $N = 1$ supersymmetry were analysed. The structure of D-terms in $N = 1$ orientifold compactifications with fluxes was elucidated, and the consistency conditions on gauged symmetries and general fluxes coming from brane-localized Bianchi identities were

derived. The low energy supersymmetry breaking from flux compactification has been analysed. Moduli stabilization in de Sitter space has also been addressed.

New tools for the construction of semirealistic string models have been presented. A search of new $N = 1$ 4D Minkowski vacua in string theory has been carried on. The supersymmetric standard model has been obtained from a Z_6 orbifold compactification of the $E_8 \times E_8$ heterotic string, with no extra exotic particles and a natural hierarchy between the top and other Yukawa couplings. A complete classification of Z_N orbifold compactifications of the $SO(32)$ heterotic string was given, showing that interesting possibilities for model building also arise in this case. More models with intersecting branes were constructed. Using free fermionic construction techniques, about 10^{10} string vacua were classified, while 15% of them have three chiral families.

Progress was made towards the realization of gauge mediated supersymmetry breaking in string theory. This was based on local Calabi-Yau geometries with two isolated singularities at which systems of D3- and D7-branes are located, corresponding respectively to the visible and hidden sectors, with supersymmetry broken at a meta-stable minimum. The scenario with split extended supersymmetry was also further understood. In these models supersymmetry is broken by small deformations of intersection angles of D -branes, leading to tree-level scalar masses m_0 . By an explicit one-loop string amplitude computation, gauginos were shown to acquire hierarchically smaller Dirac masses of order m_0^2 in string units. Furthermore the one-loop Higgsino mass was shown to be of order m_0^4 .

The effective theories of low scale orientifold models with anomalous $U(1)$ s have been analyzed. Probe D -brane dynamics in diverse backgrounds was explored. Non-factorizable D -branes on products of cosets, and their relation with permutation branes, were studied. The electroweak symmetry breaking was studied in orbifold compactifications of the heterotic string with continuous Wilson lines. The moduli dependence of the Kähler potential of chiral matter fields for Calabi-Yau compactifications was extracted in a perturbative expansion. The recently proposed "mirage mediation" of supersymmetry breaking was shown to have attractive phenomenological features, among which smaller fine tuning for obtaining the observed electroweak symmetry breaking scale. A study of string compactifications with Randall Sundrum throats has led to a new determination of the likelihood of obtaining the Standard Model in the string Landscape. Finally, possible consequences from having a large landscape of vacua, such as occurs in string theory, were investigated. In particular the possibility was explored that the anthropic probability factors should include a contribution that depends on the amount of inflation that occurs in the various patches of the universe. This could have an enormous effect on the selection process.

e) Extra dimensions, KK phenomenology and gravity modifications
(Palaiseau, Saclay, Bonn, Greece, INFN, Trieste, Madrid, Oxford, Warsaw, CERN, US team)

Several aspects of the higher-dimensional theories were investigated, such as Kaluza-Klein (KK) phenomenology and gravity modifications. Six dimensional brane world scenarios were explored and gauge fields, fermion masses and mass gap was obtained. The renormalization of the gauge couplings in supersymmetric five and six dimensional non-Abelian gauge theories coupled to hypermultiplets compactified on orbifolds to four dimensions has been computed. A model with 4D brane-localized Higgs type potential of a 6D scalar field satisfying the Dirichlet boundary condition on the boundary of a transverse 2D compact space has been studied. In a similar context, a 6D mass generation for neutrinos

living on the brane has been considered. Stability of the inter-brane distance in 5D models with branes was analytically and numerically studied. Necessary and sufficient conditions for stability were given in several cases for static and inflationary backgrounds. The study of extra dimensions and of modifications of gravity also propelled the realization that the absence of superluminal modes on arbitrary backgrounds provides a subtle but powerful constraint on effective field theories.

A detailed analysis of the flavour problem and of proton decay was performed in grand unified theories formulated in extra dimensions. Improved bounds on universal extra dimensions and constraints on KK-neutrino dark matter have been obtained. The energy emission rate for gravitons in the bulk from evaporating higher-dimensional non-rotating black holes was computed and showed a vector radiation dominance. Properties of rotating black holes in higher dimensional TeV scale gravity were analyzed and the complete radiation spectra and time evolution were calculated. The deconstruction of 5D gauge theories in the Randall-Sundrum background was carefully analyzed. Theory of q -Bessel functions was used to prove explicitly that 5D theory can be approximated by deconstruction in all its perturbative range.

The detection of gravitational waves associated to first order phase transition in the early universe was studied in new models of the electroweak symmetry breaking. The gravitational wave signal generated by the cosmological phase transition into a warped space-time geometry was found to be detectable at the planned space interferometer, LISA. The possibility that the unprecedented precision of atom interferometry can lead to laboratory tests of general relativity to levels that may rival or exceed those reached by astrophysical observations was explored. An experiment was proposed that within one year can test the equivalence principle several orders of magnitude better than the current limit and also probe general relativistic effects, such as the non-linear three-graviton coupling. Finally, multi-graviton theories have also been considered.

f) Dualities and non-perturbative effects
(Palaiseau, Saclay, Bonn, INFN, Trieste, Oxford, CERN)

Generalized compactifications on manifolds with $SU(3)$ structure have been investigated. Perturbative and non-perturbative dualities in such compactifications have been studied. This also considerably enhanced the understanding of $N = 4$ and $N = 2$ supergravities. Comparing the low energy effective actions, a form for the manifolds with $SU(3)$ structure was proposed which are dual to the heterotic setup with two-form fluxes turned on. Six dimensional flux compactifications have been used to generate standard 4d gravity on a brane. A better understanding of $N = 1$ 4D supergravity potentials arising from fluxes and gaugino condensate has been obtained. A new and efficient method to systematically analyse 4D effective supergravities which descend from flux compactifications has been proposed. A novel supersymmetric solution to a non-linear sigma model coupled to supergravity has been constructed which represents an unexpected class of solutions to a 6D theory with gravity and gauge fluxes. The study of D -branes in group manifolds and NS5 branes distributions has been carried on.

Aspects of Gravity and Black Holes have been studied within the AdS/CFT correspondence. Remarkable results have been obtained with a proposal of a ‘holographic extension’ of QCD to five dimensions which seems to capture information on the hadronic spectra. A method to quantize moduli spaces of supergravity solutions was developed, allowing to study duality in specific sectors of AdS/CFT. Non-critical string duals of 4D CFTs and

gauge theories with flavors have been proposed, while supergravity with brane configurations have been considered to describe $N = 1$ SQCD or deformed SYM theories. $N = 1$ Seiberg dualities were proven by studying the dual string theory in the NS5 brane backgrounds using non-critical strings. Dual descriptions of dynamical symmetry breaking in 4D have been considered in higher dimensions. An attempt to understand the string theory which is dual to weakly coupled gauge theory was performed, aiming to study strings moving in highly curved space-time. A discrete version of string theory was developed which correctly reproduces the one-loop anomalous dimensions and structure constants in a certain sector of the $N = 4$ gauge theory. A theoretical approach for counting microstates of 4D BPS black holes has also been proposed.

Topological couplings for vector- and hyper-multiplets of closed string compactifications to 4d on Calabi-Yau manifolds have been computed using the hybrid string formalism. Closed bosonic string field theory continued to be investigated. In particular the non-perturbative tachyon vacuum at high level has been studied and the 5-tachyon contact terms have been obtained at the quintic order of the theory. A breakthrough was made towards the understanding of tachyon condensation, by considering open string field theory in a new basis, where the star product simplifies considerably. An exact analytic solution representing the non-perturbative tachyon vacuum was thus found. The computation of the energy difference between the perturbative and non-perturbative vacua, analytically proves Sen's conjecture.