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Mass hierarchy and particle physics at the TeV scale

Acronym: MassTeV

Duration: 60 months

Proposal summary

The research goal of this proposal is the investigation of the most fundamental aspects of particle physics models and gravity at high energies, and establishing the connection between these findings and experiments. The main fundamental questions that will be addressed are: What is the origin of mass for the mediators of the weak interactions and its connection with the masses of quarks and leptons? Why this mass is \textit{hierarchically} different from the Planck scale which makes gravity so weak compared to the other three known fundamental interactions described by the current Standard Model of particle physics? Why this enormous mass hierarchy is quantum mechanically stable? What is the theory that describes physical laws at TeV energies which will be explored in the near future by the Large Hadron Collider at CERN? These questions are at the very frontier of knowledge of theoretical particle physics and phenomenology and their intersection with gravity and string theory.

All members of the proposed research team have made breakthrough contributions in putting forward and developing new ideas that dominated such a research during the past 10 years. Although there is a certain overlap in the interests, each member brings a different unique expertise to the research, which will strongly resonate with the other members activity. Obviously, this project is strongly correlated with LHC physics confronting theoretical predictions with observations and using experimental data for building new theories and correcting existing models. In such an intense dynamical process, participation of doctoral students and postdoctoral researchers will be absolutely crucial and their active involvement is an essential component of the project. The main funding required by the project from the EU is for hiring of 15 person-years of PhD students and 17 person-years of postdocs.
Section 1b: Extended Synopsis of the project proposal

High Energy Physics studies the elementary constituents of matter and their fundamental forces. It is one of the basic areas of forefront research in exact sciences with a large potential and spectrum of applications that improve continuously human life and civilization. The experimental tools for such a study are particle accelerators operating at very high energies that allow to extract the physical laws of Nature at very short distances. Their theoretical description is on the other hand realized in terms of modern mathematical theories encoding the symmetries of physical phenomena and characterized by internal simplicity and predictive power. Today all known forces, excluding gravity, are described very accurately by the so-called Standard Model of Particle Physics, which is a quantum field theory based on the symmetry principle of local gauge invariance. This theory correctly accounts for all the currently existing experimental data in particle physics. However, the Standard Model provides us with big mysteries. Why is the weak interaction force (responsible for radioactive decays) mediated by the massive messengers, W and Z bosons, whereas all the other known forces of nature (including gravity) are mediated by the massless ones? How is this mass gap generated, and what is the connection with the masses of quarks and leptons? In fact, understanding the origin of the weak interaction scale is only half of the problem. Perhaps even bigger mystery is the quantum stability of this mass scale relative to the Planck mass, the scale of the gravitational interaction. These are actually the main fundamental questions that will be addressed by the proposed project.

Presently, High Energy Physics undergoes a critical and historic moment with the start in operation of the Large Hadron Collider (LHC) at CERN late 2008. LHC, which was in preparation for about 20 years, is a spectacular technological achievement, the most powerful particle accelerator that was ever built. Using superconducting magnets at a temperature of just 1.9 degrees above absolute zero, colder than outer space, it will accelerate protons to more than 99.9% the speed of light, colliding at a center of mass energy of 14 teraelectronvolts (TeV). Having an expected operational lifetime of about 20 years, it will allow to explore the structure of matter at distances of order $10^{-19}$ meters, almost 100 times shorter than those reached previously. What are the major expectations for this structure?

First, LHC will probe the so-far-missing building block of the Standard Model, which is responsible for the generation of the weak interaction scale and of the masses of elementary particles in general. This building block is either an elementary Higgs boson, or whatever physics that replaces it. Secondly, there are widely-accepted excellent theoretical arguments suggesting that LHC should also be able to probe the new physics, that is responsible for the mysterious quantum stability of the Higgs mechanism, an inexplicable smallness of the weak scale relative to the Planck mass. It should be stressed, that the latter statement is motivation for the searches of most of the Beyond the Standard Model physics at LHC. The existence of Dark Matter in the Universe is an additional argument in favor of new physics at this scale.

Our project is strongly correlated with the LHC physics: on one hand, it will use continuously the experimental data and possible discoveries to test theoretical ideas and models, while on the other hand it will predict new phenomena and provide theoretical stimulus to the experimental program. The project will also benefit from the location of the research team members at CERN, in a close proximity with the experimental colleagues, that will allow for a more efficient exchange of the ideas.

The fundamental questions addressed are at the very frontier of knowledge of High Energy Physics.
Physics and particle phenomenology and their intersection with gravity and string theory. Correspondingly, the proposal has highly ambitious objectives, that go well beyond the current state of the art. Both the questions and challenges addressed and its far reaching goals are well justified, given the high quality and the research abilities of the team members, their previous breakthrough achievements and the very special timing in the field.

The last decade or so was characterized by a rapid theoretical progress in understanding the possible nature of the above-mentioned new stabilizing physics. Some of the most profound ideas were put forward that established a connection between the world of particle phenomenology at the TeV energy and such seemingly-remote and fundamental concepts as string theory, quantum gravity and extra dimensions. Not only these ideas opened up new horizons in theory, but they gave an obvious new meaning to LHC.

A major strength of the proposal is the extremely high quality of the research team and their suitability for the proposed research. All members have made breakthrough contributions in putting forward and developing different aspects of the new ideas, such as TeV\(^{-1}\)-size extra dimensions, TeV scale string theory and quantum gravity (realized either through Large Extra Dimensions, or through more recently suggested large number of species), low scale unification from extra dimensions, extra dimensional models that replace the Standard Model Higgs, etc. Although there is a major overlap in the interests, each member brings a different unique expertise to the research, which will strongly resonate with the other members activity.

Since the proposed research deals with the most fundamental aspects of nature, with the particular emphases on LHC physics, the potential scientific and scholarly impact is expected to be extremely strong. The project will also have a very strong interdisciplinary impact for Cosmology and Astrophysics. The upper bound of the total impact is currently hard to estimate, as it can be enormously enhanced in case of positive experimental outcome at LHC.

Another important aspect of the scholarly impact is involvement of students and postdocs in our research, which is an essential component of it. Also, our findings are constantly reported at the summer schools and at the invited university or the public lectures. The latter aspect is an important point in the intellectual exchange with representatives of the other fields, and for popularization of science in general.

The high LHC priority to determine the origin of the electroweak scale, makes it compelling to analyze the different mechanisms addressing electroweak symmetry (and possibly supersymmetry) breaking and approaches to the hierarchy problem with novel TeV physics, and to undertake a detailed analysis of their phenomenological consequences. More precisely, the main objectives of the project are:

1. Various approaches to the hierarchy problem, such as supersymmetry, strong dynamics, extra dimensions, TeV strings, large N species, etc. These should be confronted with the future LHC data, leading to a discrimination between different field theory and string theory models and their specific signatures.

2. Parametrizing the effects of new physics in the (multi)TeV range by effective higher-dimensional operators added in the Standard Model or in its minimal supersymmetric extension (MSSM). An analysis of the effective field theory in terms of MSSM fields including these operators can then be performed in a model-independent way. Note that in case if the LHC would not reach a threshold of new particle creation, effective operators will become the main probe of the new physics. On the other hand, a study
of more detailed consequences of various mechanisms of mediation of supersymmetry breaking, such as gravity, minimal and/or generalized gauge mediation, or hybrid models is important from the point of view of recent progress on constructing simplified models of supersymmetry breaking.

3. String phenomenology. A complete and explicit model of moduli stabilization with small positive vacuum energy is a goal that can be achieved in a technically controllable way. Imprints of moduli fields will be studied in early cosmology, but also at low energy in colliders, through their effects on the particle spectra, interactions and decay channels. String models with moduli stabilization have, in addition to the Standard Model particles and moduli fields, additional exotic states and interactions that can be light enough to give effects at LHC. Moreover, we plan to perform explicit string model building with high or low string scale and analyze in detail the resulting phenomenological consequences.

4. Modification of gravity at short and long distances and their cosmological implications. Some of the approaches to the hierarchy problem, notably extra dimensional models, also predict modifications of gravity at short and long distances, a different cosmology at early time and various astrophysical effects. Further work is needed however to check internal consistency of some of these proposals and their low-energy consequences, most notably models describing infrared modifications of gravity.

Shortly, the main goal of our project can be characterized as investigation of the most fundamental aspects of particle physics models and gravity at high energies, and establishing connection between these findings and experiment. The strategy and methodology of the proposed research includes different components. On one hand we will of course continue generating new theoretical ideas and studying their theoretical consistency and impact both for fundamental physics and for phenomenology. On the other hand, once the LHC data will become available, an important component of our research will become a “live” phenomenology. We shall confront the existing theoretical predictions with observations, as well as use experimental data for building new theories and correcting the existing models. This will be an intense dynamical process, in which participation of postdocs and graduate students will be absolutely crucial. Thus, conducted research is performed in two simultaneous general directions, which can be defined as the “Model Building” and “Phenomenological Studies of the Models”. In each direction, our methodology includes several simultaneous strategies:

- **Top-Down Approach**, based on direct theoretical studies within the most fundamental microscopic framework, such as string theory, and on building consistent unified theories of particle physics and gravity directly within such a framework, in combination with extremely detailed phenomenological analysis. The latter includes deriving the direct phenomenological predictions of microscopic theories, and confronting them with the existing experimental data, both in particle physics and in cosmology. This provides a powerful guideline, both for immediately ruling out the observationally-inconsistent models, and also for classifying the surviving models according to their level of “naturalness”.

- **Bottom-Up Approach**, based on investigating theoretically-motivated consistent ultraviolet completions of the Standard Model (that is, embedding in a more complete microscopic framework), mostly incorporating effective field theory techniques and the same fundamental principles as in top-down approach. A crucial aspect of phenomenological studies of the Bottom-Up method is not just confrontation with an existing data, but understanding of what we should see in new experiments, and in particular at the LHC. The ultimate
task is to convert the theory predictions into concrete experimentally-recognizable events. It is also very important, whenever it is possible, to isolate the generic model-independent aspects of a given signature.

Both methods have undeniable advantages, and the combination of the two approaches maximizes the success of our research. For example, the advantage of the top-down approach is, that working in a well defined microscopic framework guarantees the consistency of the derived model. At the same time, the bottom-up strategy enables us to focus on and study an ultraviolet completion of some given key phenomena, putting aside secondary technical complications of the fundamental framework.

- General consistency considerations play also a crucial role in theory building. Well known examples of such consistency requirements are exact gauge symmetries, cancellation of anomalies, absence of negative norm states in the theory, etc. Such considerations are extremely useful guidelines, and will be full-scale employed in our studies. Due to their obvious power in constraining Beyond the Standard Model physics, intelligent application of the consistency requirements and derivation of new bounds will be an essential part of our methodology.

The main intermediate goals (milestones) relevant for the research objectives are:

1. Uncovering the Higgs particle: analyze possible experimental evidence at the LHC and compare with models going beyond the Standard Model, such as supersymmetric extensions, composite Higgs, little Higgs, higher dimensional theories and low scale strings.

2. Single out the most relevant collider signatures of various models, either in direct production of the new states or in indirect probes via deviations in Standard Model observables.

3. Implement or propose new methods to determine the spin of new particles beyond the Standard Model. This will be of prime importance to discriminate among various schemes to stabilize the weak scale, such as supersymmetry, little Higgs with T-parity, low scale string theory, TeV extra dimensions, large number of particle species etc.

4. Flavour structure: analyze the LHC data to constrain the flavour structure of the physics at the TeV scale and above. On one hand, try to understand if the mechanism at work for the stabilization of the weak scale can naturally account for the smallness of flavour changing neutral currents, while on the other hand discriminate between scenarios with an anarchic structure of Yukawa couplings from models with flavour symmetry among the three generations of quarks and leptons.

5. Dark matter: establish whether the identified models of electroweak symmetry breaking can naturally account for dark matter and if so, work out the dark matter signatures at the LHC, direct detection and indirect detection experiments.

6. High temperature expansion: determine, for each class of models, the nature of the electroweak phase transition.

7. Supersymmetry breaking: if supersymmetry is found at the LHC, we will need to determine its breaking mechanism and understand its mediation to the observable sector.

8. Confront the string theory description of particles and their interactions with the LHC data. A major task is the construction and study of phenomenologically viable models. In particular, analyze the structure of the couplings which determine the pattern of fermion masses and mixings, including neutrinos. Explore the origin of supersymmetry and gauge symmetry breaking in compactified string theories in the presence of fluxes.
9. String cosmology; in particular, study of cosmic strings and string inflation models.

10. Confrontation with astrophysical and cosmological data, which are also a natural labora-
tory to test models of modified gravity at both large and short distances.

11. Microgravity experiments: follow any experimental progress on that direction and com-
pare the resulting constraints on the string scale and the size of extra dimensions to the
ones obtained from colliders and from cosmology.

The research team is formed by participants of two institutes: CERN and Ecole Polytech-
nique (EP). Besides the PI, there are two key senior members at CERN: Gia Dvali (GD) and
Christophe Grojean (CG) contributing half of their time to the project, and one at EP: Emilian
Dudas (ED) contributing full time as the PI. GD joined CERN recently and is working in the
interface of high-energy physics, cosmology and astrophysics. CG is working mainly on aspects
of new physics beyond the Standard Model, focusing on problems directly connected to LHC
experiments. ED is working on a large spectrum of physical theories beyond the Standard
Model, varying from phenomenology of supersymmetry and extra dimensions to string theory.
Together with the PI, they have all collaborated in the past and made world-leading break-
throughs. They bring essential and complementary expertise necessary for the achievement of
the project objectives.

Moreover, the project will hire PhD students, postdocs, and some visitor scientists and
experts that are described below.

1. The PhD students are needed for CERN, which has no proper funds for supporting
doctorate theses in theoretical physics. We ask for five 3-year PhD positions during the
project duration (one for the first year and two for the second and the third), making a
total of 15 years of student funding.

2. On the contrary, EP has sufficient national funds for supporting PhD students but very
limited regular budget for postdocs. We ask for one 3-year post-doctoral position per
year for the first three years of the project and one 2-year position for the fourth year.
This gives a total of 11 years of post-doctoral funding for EP. Moreover for CERN, we
ask the funding of one 2-year post-doctoral fellow for the second, third and fourth year
of the project, giving a total of 6 years post-doctoral funding for CERN (with particular
focus on non-member states where the local budget is very limited).

3. We also ask some funds to support a certain number of long term visitors and experts
with an average stay of a few months: 6 months visitor salary yearly at each institute,
that makes a total of 60 months for the project.

The estimate of the above required personnel cost is 1,598k euros: 1,011k for CERN and
587k for EP. In addition to the personnel costs that constitute the main part of the budget, some
other direct costs are needed to finance mainly travel and subsistence expenses. The estimate
for these other direct costs is 485k euros: 280k for CERN and 205k for EP. The overheads are
set to 20% of the direct costs. The total requested EU contribution for the project is therefore
2,499,600 euros: 1,549,200 for CERN and 950,400 for EP.

The total budget of the project includes also the salaries of the four key senior members which
is provided by the host institutes. It amounts to 4,654,704 euros, including 20% indirect costs.
Section 2: The Project proposal

i. State-of-the-art and objectives

The aim of Particle Physics is to understand the most fundamental building blocks of nature and the forces that these constituents are subjected to. Last several decades were marked by an extraordinary success in this direction. The so-called Standard Model of particle physics was created and experimentally tested. This theory correctly accounts for all the currently existing experimental data in particle physics. However, the Standard Model provides us with big mysteries. Why is the weak interaction force (responsible for radioactive decays) mediated by the massive messengers, W and Z bosons, whereas all the other known forces of nature (including gravity) are mediated by the massless ones? How is this mass gap generated, and what is the connection with the masses of quarks and leptons? In fact, understanding the origin of the weak interaction scale is only half of the problem. Perhaps even bigger mystery is the quantum stability of this mass scale relative to the Planck mass, the scale of the gravitational interaction. These are actually the main fundamental questions that will be addressed by the present project.

STATE-OF-THE-ART

One of the major actual goals of theoretical high energy physics is to uncover the origin of the electroweak symmetry breaking in the Standard Model of particle physics, which describe the electromagnetic, the weak and the strong forces. The simplest and most convincing way of realizing it is by postulating the existence of a new scalar particle, the Higgs, with specific interactions to the known elementary particles. The biggest particle physics collider in the world that will start running the next year at CERN, Geneva, the Large Hadron Collider (LHC), has as its main target the search for the new physics associated with the electroweak symmetry breaking. A guiding principle for any physics going beyond the Standard Model that addresses electroweak symmetry breaking is the so-called hierarchy problem, i.e. the understanding of the smallness of the electroweak scale (the W and the Z boson masses) compared to the large mass scales appearing in Grand Unified Theories (GUT) or compared to the Planck scale $M_P \sim 10^{19}$ GeV, which traditionally defines the scale where gravity becomes strong. The most popular theoretical constructions that will be tested at LHC and future colliders: low-energy supersymmetry, strongly-coupled technicolor-like theories and the large extra dimensional models, have all as a common ground the search for a solution to the hierarchy problem. On the other hand, quantization of the gravitational force and its unification with the three other fundamental forces can be consistently done only within the context of a finite theory; String Theory is to date the most convincing and advanced framework that includes gravity together with all other known particles and interactions.

In recent years, we have witnessed a vast amount of activity in particle physics beyond the Standard Model, both within field theory and in string theory.

- New approaches to the hierarchy problem have been proposed based on:
  - Large and flat extra dimensions, whose size is $10^{-16}$ cm if the Standard Model particles are propagating, or even of macroscopic, submm size, in the case of the dimensions where only gravity propagates. These scenarios were shown to be naturally realized within the context of String Theory with a fundamental string scale in the TeV range, giving rise to the so-called low-scale quantum gravity or the TeV string models.
- Small and warped extra dimensions, whose size is of order \(10^{-31}\) to \(10^{-32}\) cm. It was shown that such a framework is also naturally realized in String Theory, if appropriate magnetic-type fluxes along various subspaces of the six-dimensional internal space in String Theory, are turned on.

- Considerable progress, both theoretical and phenomenological, has been made on the problem of supersymmetry breaking via compactification, by using non-BPS systems and via the addition of magnetic-type fluxes in the internal space.

- New models of electroweak symmetry breaking were proposed, based on the properties of extra dimensions:
  - Models where Higgs is an internal component of a gauge field (gauge-higgs unification).
  - Models with no elementary scalar Higgs, where electroweak symmetry is broken via nontrivial boundary conditions in the extra dimensional space (higgsless models).

- In addition, TeV\(^{-1}\)-size extra dimensions were shown to be able to generate accelerated unification at low energies, whereas smaller dimensions can generate new ways of breaking grand unified gauge groups that avoid some of the problems of traditional GUT models.

As described below in the Resources subsection iii, the members of the present project were among the pioneers and promoters of the ideas uncovering this recent progress.

The impressive progress on the theoretical side was followed by detailed phenomenological studies concerning the colliders discovery potentials, table top gravity experiments and cosmological tests for the various extra dimensional and TeV strings models.

The low-energy supersymmetric models, in particular its minimal version the Minimal Supersymmetric Standard Model (MSSM) was confronted with the constraints and limits from the LEP2 collider searches at CERN. The tension between the predictions of the simplest supersymmetric models and the LEP2 results did stimulate the proposal of non-minimal extensions including additional states and/or interactions in the multi-TeV range, with specific signatures that can be uncovered by a TeV collider machine and, in a complementary way, by the new and precise measurements of the amount of dark matter in the universe and its properties.

From a more theoretical perspective, the gauge-string duality conjecture has led to new computational methods in strongly-coupled regimes of gauge theories and to new views on composite models. Moreover, warped spaces naturally arising in this context have also led to a new explanation of large hierarchies and to the novel possibility of localizing gravity even in the case of infinitely large extra dimensions.

New mechanisms for breaking gauge symmetries and supersymmetries have been successfully introduced in string theory, and have been explored in some detail in new phenomenological models, that are testable at the next generation of colliders if the fundamental string scale is in the TeV range.

Recent results on the flux compactifications of string theory have also shown the possibility of stabilizing all moduli fields, which determine the string coupling constant and the geometry of the internal space. This progress opens the way to a thorough phenomenological analysis of low-energy string models, from the viewpoint of particle spectra, collider signatures and applications to cosmology, in particular to inflation and explaining the current acceleration stage of our universe. The large number of string theory vacua and their multifaceted intrinsic properties can also suggest radically new views on string phenomenology, with possible impact
on low-energy model building and experimental signatures. Very recently, a new solution to the hierarchy problem was proposed by one of us (G.D), based on the existence of a very large number of fields which force the UV cutoff of the effective field theory to be in the TeV range. This proposal, which simultaneously suggests a new solution to the strong CP problem and contains as a particular case the low scale quantum gravity / large extra dimensional scenario, predicts the existence of new physics in the TeV range, accessible at the LHC.

OBJECTIVES

The beginning of the LHC experimental program in 2008, with its high priority to determine the origin of the electroweak scale, makes it compelling to analyze the different mechanisms addressing electroweak symmetry (and possibly supersymmetry) breaking and approaches to the hierarchy problem with novel TeV physics, and to undertake a detailed analysis of their phenomenological consequences. Despite the tremendous theoretical progress summarized thus far, extensions of the Standard Model have to successfully pass the new broad range of detailed experimental tests including proton decay, flavor and neutrino physics, electroweak precision tests as well as tests in cosmology and astrophysics. In view of the important theoretical tasks and experimental difficulties in interpreting the LHC data due to to the huge Standard Model background, we believe that a joint effort in approaching these problems is welcome and urgent.

Some of the concrete frameworks we intend to address in our project for the new physics in the TeV range are:

1. Various approaches to the hierarchy problem.
   The various approaches to the hierarchy problem (supersymmetry, strong dynamics, extra dimensions / TeV strings, large N species) need to be confronted with the future LHC data. All participants of the present project intend to use various perturbative and non-perturbative (holographic) methods to discriminate between different field-theory and string theory models and their specific signatures.

   If the new physics is in the (multi)TeV range, at lower energies its effects can be encoded in the presence of specific higher-dimensional operators generated by the virtual exchange of the new particles and interactions. Most alternatives to supersymmetric models, such as little Higgs models, models based on strong dynamics and extra dimensional higgsless models, can be parametrized at low energy in terms of higher-dimensional operators for Standard Model fields. In case if LHC would not reach a threshold of new particle creation, effective operators will become the main probe of the new physics. On the other hand, the MSSM, as mentioned before, is confronted with several difficulties. Propose and study non-minimal and well-motivated extensions is important. One approach that we intend to pursue is to assume a little energy gap between the mass scale associated to the new particles and interactions as compared to the electroweak and MSSM mass scale. Then an effective field theory in terms of MSSM fields including higher-dimensional operators encoding the effects of the non-minimal particles and interactions is possible and can be performed in a model-independent way.

On the other hand, a study of more detailed consequences of various mechanisms of mediation of supersymmetry breaking: gravity, minimal and/or generalized gauge mediation, or hybrid models could be useful from the point of view of recent progress on constructing simplified models of supersymmetry breaking.
3. String phenomenology.

All string constructions involve the presence of (moduli) fields parametrizing the string coupling and the quantum fluctuations of the internal space. Giving all of these fields a mass (moduli stabilization) plays a central role in making contact with phenomenology. As mentioned previously, major progress was made recently in achieving moduli stabilization in flux compactifications, suitably combined with additional sources of supersymmetry breaking. A complete and explicit model of moduli stabilization with small positive vacuum energy is still not available. We believe that recent progress in the computation of instantonic effects in string models, combined with moduli stabilization and supersymmetry breaking can achieve this goal in a technically controllable way. Moduli fields can leave their imprints in early cosmology, but also at low energy in colliders, through their effects on the particle spectra, interactions and decay channels. String models with moduli stabilization have also, in addition to the Standard Model particles and moduli fields, additional exotic states and interactions that can be light enough to give effects at LHC. One example that we plan to investigate are $Z'$-type gauge bosons of stringy nature, that give rise to anomalous and testable couplings at low-energy. Moreover, we plan to perform explicit string model building with high or low string scale and analyze in detail the resulting phenomenological consequences.

4. Modification of gravity at short and long distances and their cosmological implications.

Some of the approaches to the hierarchy problem, notably extra dimensional models, also predict modifications of gravity at short and long distance, a different cosmology at early time and various astrophysical effects. More work is needed however to check internal consistency of some of these proposals and their low-energy consequences, most notably models describing infrared modifications of gravity.

IMPORTANCE OF THE RESEARCH

The proposal addresses the most fundamental questions, that are at the very frontier of knowledge of High Energy Physics, and in the same time are at the intersection of theoretical particle physics/gravity, phenomenology and string theory. Correspondingly, the proposal has highly ambitious objectives, that go well beyond the current state of the art.

Both, the questions and challenges addressed by the proposal and its far reaching goals are well justified, given the high quality and the research abilities of the team members, their previous breakthrough achievements and a very special situation in the field.

We are indeed at a very special point in space and time. The Large Hadron Collider is about to start operating at CERN, and to begin probing the sub-structure of nature at unprecedented $10^{-17}$ cm distances, corresponding to the energy scales of the few TeV. What are the major expectations for this structure?

First, the LHC will probe the so-far-missing building block of the Standard Model, which is responsible for the generation of the weak interaction scale and of the masses of elementary particles in general. This building block is either an elementary Higgs boson, or whatever more exotic physics that replaces it.

Secondly, there are widely-accepted excellent theoretical arguments suggesting that LHC should also be able to probe the new physics, that is responsible for the mysterious quantum stability of the Higgs mechanism, an inexplicable smallness of the weak scale relative to the
Planck mass. It should be stressed, that the latter statement is motivation for the searches of most of the Beyond the Standard Model physics at LHC. The existence of Dark Matter in the Universe is an additional argument in favor of new physics at this scale.

The last decade or so was characterized by a rapid theoretical progress in understanding the possible nature of the above-mentioned new stabilizing physics. Some of the most profound ideas were put forward that established a connection between the world of particle phenomenology at the TeV energy and such seemingly-remote and fundamental concepts as string theory, quantum gravity and extra dimensions. Not only these ideas opened up new horizons in theory, but they gave an obvious new meaning to LHC.

The major strengths of the proposal is the extremely high quality of the research team and their suitability for the proposed research. All the members have made breakthrough contributions in putting forward and developing different aspects of the above-mentioned new ideas, such as TeV$^{-1}$-size extra dimensions, TeV scale string theory and quantum gravity (realized either through Large Extra Dimensions, or through more recently suggested large number of species), low scale unification from extra dimensions, extra dimensional models that replace the Standard Model Higgs, etc. Although there is a major overlap in the interests, each member brings a different unique expertise to the research, which will strongly resonate with the other members activity.

The project will also benefit from the location of the research team members at CERN, in a close proximity with the experimental colleagues, that will allow for a more efficient exchange of the ideas.

Since the proposed research deals with the most fundamental aspects of nature, with the particular emphases on LHC physics, the potential scientific and scholarly impact is expected to be extremely strong. The project will certainly also have a very strong interdisciplinary impact for Cosmology and Astrophysics.

The upper bound of the total impact is currently hard to estimate, as it can be enormously enhanced in case of the positive experimental outcome at LHC. Obviously, observation of any new physics (be it supersymmetry, large extra dimensions, black holes or string excitations, or something else) would be truly revolutionary, and will put our efforts in a very different perspective. Another important aspect of the scholarly impact is involvement of students and postdocs in our research, which is an essential component of it. Also, our findings are constantly reported at the summer schools and at the invited university or the public lectures. The latter aspect is an important point in the intellectual exchange with representatives of the other fields, and for popularization of science in general.

ii. Methodology

The strategy and methodology of the proposed research includes different components. On one hand we will of course continue generating new theoretical ideas and studying their theoretical consistency and impact both for fundamental physics and for phenomenology. Once the LHC data will become available, an important component of our research will become a “live” phenomenology. We shall confront the existing theoretical predictions with observations, as well as use experimental data for building new theories and correcting the existing models. This will be an intense dynamical process, in which participation of postdocs and graduate students will be absolutely crucial.
Shortly, the main goal of our project can be characterized as investigation of the most fundamental aspects of particle physics models and gravity at high energies, and establishing connection between these findings and experiment. Thus, conducted research is performed in two simultaneous general directions, which can be defined as the “Model Building” and “Phenomenological Studies of the Models”. In each direction, our methodology includes several simultaneous strategies. We shall characterize them briefly below:

MODEL BUILDING

1. Top-Down Approach.

This strategy is based on direct theoretical studies within the most fundamental microscopic framework, such as string theory, and on building consistent unified theories of particle physics and gravity directly within such a framework. The guidelines for such investigations and for the subsequent unified model building are the well tested principles of nature, such as the underlying gauge invariance, symmetries and dualities, economy and elegance. Correspondingly methodology of this approach is determined by the above-mentioned principles, and respective techniques. The main work is conducted by using the full string theory and field theory apparatus, in combination with extremely detailed phenomenological analysis.

2. Bottom-Up Approach.

This strategy is based on investigating theoretically-motivated consistent ultraviolet completions of the Standard Model (that is, embedding in a more complete microscopic framework), mostly incorporating effective field theory techniques and the same fundamental principles as in top-down approach.

Given the current state of the art, both methods have undeniable advantages, and the combination of the two approaches maximizes the success of our research. For example, the advantage of the top-down approach is, that working in a well defined microscopic framework guarantees the consistency of the derived model. In the same time, the bottom-up strategy enables us to focus on and study an ultraviolet completion of some given key phenomena, putting aside secondary technical complications of the fundamental framework.

For an illustration of the complementarity of the two approaches, we can consider a widely appreciated phenomenon in theories with (large) extra dimensions, such as localization of particles on branes. Existence of extra space dimensions is essential for a consistent formulation of String Theory. The size of these dimensions can be much larger than the fundamental length scale, and even be macroscopic. The reason why these dimensions stay invisible is because all the visible matter particles (quarks and leptons), as well as all the known non-gravitational forces, are confined to a lower 3-dimensional surface, the so-called brane.

In a top-down approach, branes emerge as well defined constituents of string theory with very specific mathematical properties. For example, their role can be played by D-branes on which open strings can end, or by some other field theoretic solitons. At the same time, when studying the localization of modes in bottom-up approach, one can abstract from the specific properties of the brane, and only focus on most essential effective field theory properties of it. This enables to understand generic properties of localization, that are essential for a low energy observer.
3. General consistency considerations.

General consistency considerations play crucial role in theory building. Well known examples of such consistency requirements are exact gauge symmetries, cancellation of anomalies, absence of negative norm states in the theory, etc. Such considerations are extremely useful guidelines, and will be full-scale employed in our studies.

Due to their obvious power in constraining Beyond the Standard Model physics, intelligent application of the consistency requirements and derivation of new bounds will be an essential part of our methodology. The techniques for such an application will involve both a direct microscopic analysis of a system, such as the screening of any candidate model on the absence of instabilities (ghost, tachyons) or of hidden anomalies, as well as more indirect searches for inconsistencies that are deeper buried. An example of the latter hidden constraint can be a recently-derived back hole bound on masses and number of particle species. Another example of hidden inconsistencies can be the presence of instabilities on certain curved backgrounds, in a seemingly healthy model. The example of the latter is provided by a theory of a (single) massive graviton.

PHENOMENOLOGY

Phenomenological studies are the essential component of our research, as they provide a direct bridge between the fundamental theoretical investigations and the experiment. The methodology of this approach, thus, will be adjusted accordingly to the methodologies of the model building.

1. Phenomenology of Top-Down Approach.

This includes deriving the direct phenomenological predictions of microscopic theories, and confronting them with the existing experimental data, both in particle physics and in cosmology. This provides a powerful guideline, both for immediately ruling out the observationally-inconsistent models, and also for classifying the surviving models according to their level of “naturalness”. Correspondingly, the phenomenological constraints give possibility of correcting false models, when this is possible.

Complexity of phenomenological studies is very important, since the crucial information usually comes from wide range of data. For example, new physics can be constrained by: precision electroweak observables, rare flavor-violating processes, atomic physics experiments (searches for the electric dipole moment of neutron and other sources of CP violation), astrophysical processes (such as energy loss in the star cooling), cosmology (e.g. nucleosynthesis, particle overproduction during reheating after inflation, over-closure of the Universe by the relics), precision gravitational measurements (such as violation of the equivalence principle, anomalous planetary motion and perihelion precession), or precision cosmology (distant supernova surveys, CMB studies, weak lensing, gravity waves).

2. Phenomenology of the Bottom-Up

This method allows to minimally disturb the existing phenomenological success of the Standard Model, and to focus on a limited number of new phenomena given by a minimal extension. Obviously, also here every new phenomenon has to be confronted with the complex observational data listed above.
Of course, the crucial aspect of phenomenological studies is not just confrontation with an existing data, but understanding of what we should see in new experiments, and in particular at the LHC. The ultimate task is to convert the theory predictions into concrete experimentally-recognizable events. For the latter task the combination of analytic and computational methods will be very essential.

It is very important, whenever it is possible, to isolate the generic model-independent aspects of a given signature. For example, one can imagine many models with TeV compact extra dimensions, but they all predict tower of Kaluza-Klein particles. Analogously, in string compactifications, the string vibration spectrum has certain common generic properties. Isolation of model-independent signatures allows to catch essential features of large class of theories, and to bypass a danger of being lost in model-dependent artifacts.

The first collisions at the LHC are expected in the second half of 2008. Our strategy will of course depend on the LHC results and will be adapted according to any potential breakthrough hopefully occurring during the period covered by this grant. Still, we can identify particular goals (milestones) relevant for the objectives described in subsection i.

1. **Uncovering the Higgs particle.** We want to analyze possible experimental evidence at the LHC and compare with models going beyond the Standard Model, such as supersymmetric extensions, composite Higgs, little Higgs, higher dimensional theories and low scale strings. In particular, we will extract the main classes of models that pass all experimental tests to be further considered for phenomenological studies. One aspect of the work will be to construct effective actions that capture the main structure of these theories. This will reduce the number of parameters for the analysis and allow us to treat more easily a larger class of models.

2. **Analysis of collider signatures.** We will single out the most relevant collider signatures of the model identified in (1), either in direct production of the new states or in indirect probes via predicted deviations in Standard Model observables. The goal is to be able to reach independence to test signatures of the various models and simulate ourselves LHC events. This does not replace the work done by experimentalists as the full detector simulation will not be perfectly taken into account. This however can provide a reasonable analysis. If the output is promising, we will judge whether the model and signatures under consideration deserve further detailed investigation. Information will be passed to experimentalists willing to search for these signals.

3. **Spin determination.** We will need to implement or propose new methods to determine the spin of new particles beyond the Standard Model. This will be of prime importance to discriminate among various schemes to stabilize the weak scale: supersymmetry, little Higgs with T-parity, low scale string theory, universal extra dimensions, large number of particle species etc

4. **Flavour structure.** We will analyze the LHC data to constrain the flavour structure of the physics at the TeV scale and above. We have two objectives in mind: (i) understand if the mechanism at work for the stabilization of the weak scale can naturally account for the smallness of flavour changing neutral currents. (ii) discriminate between scenarios with an anarchic structure of Yukawa couplings from models with flavour symmetry among the three generations of quarks and leptons. Many models beyond the Standard Model
predict new sources of CP violation which have direct implications for the physics of the K and the B meson systems, as well as for the electric dipole moments of the nucleons and leptons. We will seek to implement a systematic study of such effects at the LHC with the goal of elucidating the origin of quark and lepton masses and mixings.

5. **Dark matter.** We will establish whether the identified models of electroweak symmetry breaking can naturally account for dark matter and if so, we will work out the dark matter signatures at the LHC, direct detection and indirect detection experiments. In parallel, we will explore the possibility that electroweak (EW) symmetry breaking is triggered by the dark sector and we will investigate what are the necessary couplings between dark matter and the Higgs sector.

6. **High temperature expansion.** For each class of models, we will determine the nature of the EW phase transition. The scalar Higgs potential was calculated in most models of interest but its behavior at high temperature was not and this entirely remains to be done. The dynamics of the phase transition will shed light on the way of the matter-antimatter asymmetry might have originated from. For instance, a first-order phase transition will strongly favor models of electroweak baryogenesis.

7. **Supersymmetry breaking.** If supersymmetry is found at the LHC, we will need to determine its breaking mechanism and understand its mediation to the observable sector. We will identify the pattern of the soft supersymmetry breaking terms and study whether R-parity is broken.

8. **String phenomenology.** We want to confront the string theory description of particles and their interactions with the LHC data. Crucial to the string theory description is the compactification needed to leave just four flat space-time dimensions and work will be devoted to the construction and study of phenomenologically viable models. One major task will be to analyze the structure of the couplings which determine the pattern of fermion masses and mixings, including neutrinos, both in new D-brane constructions and in the perturbative and non-perturbative heterotic string compactifications. Related to this is the study of moduli stabilization and their role in determining the low-energy theory. Analysis of the LHC results is likely to shed light on the question whether the string scale is high, close to the Planck scale, or low, perhaps close to the electroweak breaking scale. Also we will explore the origin of supersymmetry and gauge symmetry breaking, in compactified string theories in presence of fluxes. Moreover, we will study the implications for the dynamics of supersymmetric field theories and string theory using various duality symmetries that relate the weak and strong coupling regime of two theories. In this, emphasis will be given to the study of the AdS/CFT correspondence between four-dimensional gauge theories and string theories in non-trivial backgrounds.

9. **String cosmology.** String theory provides a unique way to approach the quantum regime of gravity and therefore gives us tools to study the initial Big-Bang singularity. Cosmology can also be used to indirectly probe string theory. Although almost any signal that can arise in a string model can arise in a suitable low-energy effective quantum field theory, there are still two avenues for a possible cosmological test of string theory. In fortunate circumstances, some phenomenon does not fully decouple at low energies; cosmic strings, which are topological defects, are an important example. Another way to use cosmological observations to constrain string theory is to check for signals which are
natural or generic in string-derived effective Lagrangians, but highly unnatural from a conventional field-theory viewpoint. As an example, in many string inflation models, the primordial tensor signal is very small. Hence, an observation of primordial tensors would eliminate the great majority of presently-known string inflation models. The presence of branes in string theory offers a novel way of doing inflation such as through the relative motions of branes. This idea of brane inflation was put forward by one of us (GD) and generated a lot of developments. We want to study the feasibility of brane inflation in the models of string phenomenology identified in (8). Our work will therefore concentrate on these two topics: cosmic strings and construction of string inflation models.

10. **Confrontation with astrophysical and cosmological data.** While the LHC is expected to reveal new physics at the TeV, it will only be possible to guess the role this new physics played in the cosmological history of the Universe. More direct clues will come from the confrontation with results from the WMAP and Planck satellites and other (existing or future) experiments like Auger, GLAST, LISA, SNAP. Predictions for density perturbations, dark matter profiles, dynamics of dark energy will be analyzed in detail. Astrophysical and cosmological data are also a natural laboratory to test models of modified gravity at both large and short distances.

11. **Microgravity experiments.** As emphasized by two of us (IA and GD), low scale string theory could significantly affect gravitational interactions at submm distances. Therefore, tabletop experiments which aim to probe classical gravity at short distance could actually provide glimpses on the quantum regime of gravity. We will definitively keep an eye on experimental progress on that direction and we will compare the constraints on the string scale derived from these experiments to the ones obtained from colliders and from cosmology. Moreover, it has recently been noticed that atom interferometry could improve by several orders of magnitude the bounds for deviations from the Newton law: for sure, this is a direction we want to further investigate.

Tasks (1, 2, 3 and 4) are directly tight to the LHC operation and the close proximity to experimentalists at CERN will be a tremendous asset. Engaging young students and postdocs on these projects will offer them the unique opportunity to acquire dual expertise at the frontier between theory and experiment, which will be a real asset during all the LHC area. These tasks will be followed in the order presented.

Tasks (7,8 and 9) are more theoretical and will be conducted in parallel to (1–4). They are good examples of projects to be conducted in the Top-Down methodology described above. While (9) is rather independent, it would be natural to first tackle (8) before working on (7). However, positive discoveries at the LHC could force us to reverse this order.

Tasks (5,6,9, 10 and 11) are interdisciplinary and illustrate the cross-fertilization between high energy physics and other branches of science. (6) requires the knowledge of the Higgs couplings, whose determination requires a large accumulated luminosity. (5) and (10) can be conducted using existing data from already operating experiments but it is believed that the launch of the Planck satellite in the second half of 2008 will provide further impetus to these tasks. In any case, the LHC-cosmology complementarity has to be studied now, in order to help the preparation of the physics program of the next generation of big experimental program (International Linear Collider, Joint Dark Energy Mission, LISA etc).