Project description

C1. *Scientific context and motivation*.

The overall objective of the project is to look for signatures of quantum gravity and physics beyond the Standard Model of particle physics via BH production at the LHC, in ultra high energy cosmic rays data, and separately via the available data in the neutrino sector. BH production in the TeV range would be a clear signature of physics beyond the Standard Model. It is also possible that the discrepancies which exist in the neutrino oscillations data are generated by physics beyond the Standard Model effects.

The startup of the Large Hadron Collider (LHC) enables the scientific community for the first time to search for new physics in the TeV range. Besides looking for the discovery of the Higgs boson, the LHC will shed light on many questions and theoretical models which involve physics beyond the Standard Model, and this will enable us to learn more about the ultimate structure of the fabric of space-time. Models involving extra dimensions can be probed by searching for the fundamental scale of gravity. Another open question that a quantum theory of gravity is confronted with is whether a fundamental length scale exists. The possibility for the scale of gravity being within the reach of the LHC has many implications on what the data will look like. For instance in this context BHs can be created at the LHC. This leads to several other open questions: Can the signatures of their decay be observed? Is it possible that they are long lived and escape detection carrying out large amounts of missing energy? What is the effective dimensionality of space at the length scale which is probed by the LHC and how does it affect the way in which the LHC data will look like? Another open question is whether a fundamental length scale, as proposed in non-commutative theories, exists.

It is not only at the LHC where the possible existence of BHs with masses in the TeV range can be probed. If microscopic BHs exist, they are also produced when Ultra High Energy Cosmic Rays (UHECR) strike the Earth's atmosphere. The Pierre Auger Observatory has been designed to investigate the origin and the nature of UHECRs and consists of an array of about 1600 surface stations covering an area of 3000 km^2 for detecting the secondary particles of the air shower at ground level by means of the Cherenkov radiation and 24 air fluorescence telescopes are overlooking the ground array. This “hybrid” detection mode can detect particles with energies even above 10^{20} eV. At present it has 69 events above 10^{18} eV from a total of approximately 20000 events taken till December 2009 [1]. In addition to hadrons and photons the Auger Observatory is also sensitive to ultra high energy neutrinos with energies above $\sim 10^{17}$ eV [2].

With the realization that neutrinos are massive, many new questions opened up: Are there only three generations of neutrinos? Is it possible that sterile neutrinos exist as gauge singlets? If so, can they take shortcuts through extra dimensions? What would be the impact of the space-time metric on the neutrino dispersion relations and oscillation probability? Can we work our way backwards and realize the exact metric starting from the available neutrino data? The puzzles in the neutrino sector do not stop here. If one overlaps the neutrino and antineutrino data one notices a very good agreement in each sector separately, but if one compares the two discrepancies appear [3]. This leads to other questions like are there neutrino-antineutrino oscillations possible? What does that imply for the CPT or Lorentz invariance?

My interests cover the research directions mentioned above and the proposed plan is to investigate some of the open questions in each of the research areas presented above.

i) Microscopic black holes at the LHC and beyond

In the context of theories with extra spatial dimensions [4, 5] in which it considered that the Standard Model fields live on our three dimensional brane while gravity can extend in the extra dimensions (bulk), the fundamental scale of gravity can be naturally lowered to the electro-weak scale $M_{EW} \approx 1$ TeV. Since BHs can exist with masses anywhere above the fundamental scale of gravity, this opens up the possibility that microscopic BHs can be produced and detected [6, 7, 8] at the LHC , or by the Pierre Auger Observatory. Among many other things, the existence of large extra dimensions and microscopic BHs will be searched for at the LHC. There are two main extra dimensional scenarios which are looked for in present: the scenario with large extra dimensions- ADD scenario [4]; and the five dimensional warped geometry theory- Randall Sundrum (RS) scenario [5]. As it will become clear in the next paragraph, there are fundamental differences between the phenomenological implications of the two.

Despite many efforts, to date, only approximate BH metrics are known on the brane for the case of the warped geometry model, with one of them being the tidal charged BH metric [8, 9, 10]. It was shown in Ref. [7] that using a specific form of the tidal charged BH metric from Ref. [9], and a specific choice of parameter values, BH lifetimes can be very long. It was then conjectured in Ref. [11] that such BHs might be able to grow to catastrophic sizes within the Earth, contrary to the picture [12] which arises in the ADD scenario [4] in which the BHs are created and decay instantaneously within the detector. This possibility was later refuted in Ref [13]. In Refs. [14, 15] the authors solved the system of equations which describe the BH mass and momentum as functions of time for various initial conditions and values of the critical mass which occur in that model. The results showed that there exists a large parameter space within which BHs can be long lived and they can escape from the detectors resulting in large amounts of missing energy. It was also shown that BH masses, and consequently their horizon radii, cannot reach large enough values for the BHs to enter the dangerous Bondi accretion regime (in which BHs at rest accrete nuclei with thermal velocity smaller than the escape velocity).

To summarize shortly the phenomenology for BHs production, time evolution, and decay is entirely different in the case of the large extra dimensions versus the warped geometry scenario. While in the ADD scenario, BHs decay instantaneously in the LHC detectors, in the RS scenario the BHs can be long lived and can escape detection. Their only sign of existence can be large amounts of missing energy or a very distinctive track in the detectors if they are charged (the charge to mass ratio would be unique). While up to present the LHC collaboration was searching for events which could suggest BHs decaying inside the detectors, it is important for the collaboration to extend their search to a wider range of possibilities and also look for events in which there are large amounts of missing energy.

The Pierre Auger Observatory already recorded many events above the TeV range of energies and a detailed analysis of their data from this perspective is something that the community should look into. This makes the scope for one of the projects included in this research proposal.

ii) Modified neutrino dispersion relations

The discovery of the neutrino oscillations phenomena led to the conclusion that neutrinos are massive. The mere fact that neutrinos are massive already takes us beyond the Standard Model of particle physics. Neutrinos are produced as flavor eigenstates, corresponding to the three lepton flavors, but travel through space as mass eigenstates. The different values of the mass eigenvalues lead to the phenomenon of neutrino oscillations. Experimentally up to present we are only able to measure mass squared differences, and not the actual values of the neutrino masses. Before the Liquid Scintillator Neutrino Detector (LSND) experiment, two independent Δm^2 were known. A third independent Δm^2 was measured by the LSND experiment [16]. This result can only be accommodated with the rest of the neutrino data if at least four mass eigenstates exist or else the result might signal some more exotic neutrino dispersion relations. The MiniBooNE experiment was built to check these findings. The collaboration found no excess at the expected energy but an excess was found at a lower energy when working in neutrino mode [17]. Data is accumulated at a slower rate in antineutrino mode (LSND was working with antineutrinos), and the MiniBooNE findings seem to confirm an excess at the same energy as it was seen by the LSND collaboration [18]. To be more exact, the two experiments did not work at the same energy but in neutrino oscillation experiments the oscillation length to energy ratio is what matters and this ratio was preserved for the two experiments. One should note that there is no standard physics explanation for a shift between the energies of the resonances in the MiniBooNE neutrino and antineutrino channels. Matter effects (the Mikheev-Smirnov-Wolfenstein effect) are negligible for neutrinos traveling through the Earth.

In light of the contradictions between the neutrino data accumulated by different experiments (for instance the LSND and MiniBooNE experiments) there are several models in which the neutrino dispersion relations are modified. Sterile neutrinos and gravitons are singlets under the gauge group of the Standard Model, and they can travel on the brane and in the extra dimensions. Depending on the metric, the geodesics for the sterile neutrinos can lie in the bulk resulting in shortcuts and the active-sterile neutrino oscillations generate new resonances [19]. In the context of the recent MiniBooNE experiment results which show a discrepancy in the low energy regime between the neutrino and antineutrino channels, the possibility of neutrino-antineutrino oscillations is well worthy to be investigated. A generalization of the neutrino oscillations Hamiltonian to include both Lorentz- and CPT-violating terms was proposed [20]. The terms which violate Lorentz invariance modify the neutrino dispersion relations, generating new resonances. By allowing for CPT-violating parameters, neutrino-antineutrino oscillations become possible. The authors studied the possibility of neutrino-antineutrino oscillations for the case of one generation. The case was then generalized using a different approach for two generations of neutrinos and antineutrinos [21]. The resonance structure which results from the diagonalization of the neutrino oscillations Hamiltonian was analyzed. The additional CPT- violating terms generate oscillations between neutrinos and antineutrinos.

Lorentz symmetry violation can also be induced by considering both the Planck scale and the speed of light as fundamental scales. The authors of Ref. [22] investigate oscillations between an active electron neutrino state and a sterile (under the weak interactions) neutrino state in a CPT- and Lorentz-violating scenario. The direct consequence is the modification of the neutrino energy-momentum dispersion relation at high energy scales (in the Planck energy regime) by terms which vanish in the low-momentum limit. The asymmetry between particles and antiparticles is due to the different energy-momentum dispersion relations. CPT invariance would imply changing the sign of the Lorentz-violating parameter. Instead CPT violation is considered and this results in different oscillation probabilities between neutrinos as compared to the same antineutrino flavor. To solve the puzzles which appeared in neutrino physics, the neutrino sector in an extended Standard Model is also analyzed [23]. A minimal version of the ESM with two CPT-violating parameters is considered. Dispersion relations with neutrino-antineutrino asymmetry are obtained.

C2. *Objectives*.

Specifically the following research goals are going to be pursued:

A) In order to constrain the parameter space for the tidal charged BHs, I propose an analysis of the time evolution for the mass of BHs which can be produced when UHECRs strike the surface of extremely dense astrophysical objects such as neutron stars;

B) On a related but separate topic, I intend to include the case of tidal charged BHs into the BlackMax event generator;

C) A search for possible signatures of TeV BHs in the data accumulated by the Pierre Auger

Observatory;

D) Deeper analysis of the LSND and MiniBooNE anomalies. Further search for possible modifications of the neutrino dispersion relations, the possibility of neutrino-antineutrino oscillations, and for the implications of these possibilities. Detailed phenomenological analysis of the neutrino data for the case of neutrino-antineutrino oscillations.

The research ideas which will be developed throughout the duration of the present research proposal will not be limited to the ones specified above. In scientific research new ideas are continuously developed from old ones or as a result of research collaborations.

C3. *Method and approach*.

The amount of time proposed for the development of each of the points specified in the following paragraphs is an estimate and for simplicity it takes into account the entire team. The present research project proposes a duration of three years (36 months). For more information see Section C5. “Resources and budget”.

A) If BHs are produced at the LHC they propagate through the Earth after they escape from the detectors, and through vacuum after they leave the Earth. Before the BHs enter the Bondi accretion regime, the accretion rate is proportional to their velocity and to the density of the material through which they travel. For instance after the BHs leave the Earth they travel through vacuum, accretion turns off, and they only evaporate. The BHs decay mostly on the brane via Hawking radiation. For microscopic BHs it is appropriate to use the microcanonical ensemble when evaluating their evaporation rate. The time evolution of the BHs mass is computed by evolving in time the sum between the accretion and evaporation rates. I propose to analyze the time evolution of the mass for tidal charged BHs which are produced in environments with extreme densities like for instance in neutron stars. While their evaporation is described by the same mechanism (Hawking radiation) as when produced on Earth, the accretion mechanism is entirely different when the BHs travel through a dense material such as the Fermi gas inside a neutron star. The study of the time evolution for BHs which are created due to the impact of an UHECRs with particles on the surface of neutron stars will allow us to impose bounds on the free parameters from the tidal charged BHs metric.

Using proposed population of extragalactic sources for UHECRs [24], we can predict the flux of the cosmic rays arriving in our Galaxy. Also, with the help of star population synthesis codes like N-body simulations (e.g. NBODY6) or their publicly available simulations data (e.g. http://astronomy.swin.edu.au/~jhurley/nbody/archive.html), we can estimate the neutron star populations in our Galaxy. We plan to use existing GPU (Graphics Processing Unit) powered supercomputers to run our N-body simulations as this new technology can be used by the NBODY6 code and replaces special designed hardware like the GRAPE-6 interface with a CUDA library to utilize GPUs. This procedure will provide us with a theoretical prediction for the population of BHs created due to the impact of UHECRs with particles on the surface of a neutron stars.

In the end we will discuss the implications of these bounds on the possibility of BHs production at the LHC. The concrete proposed time line is as follows:

- Analytic study of the accretion mechanism (2 months);
- Numerical evaluation of the BHs mass evolution in extreme conditions (2 months);
- Evaluation of the galactic flux of UHECR and of the neutron star populations (3 months);
- Discussion of the implications on the parameter space for the tidal charged BHs metric (2 months).

B) BlackMax is a BH event generator which simulates the experimental signatures of microscopic and Planckian BH production and evolution at proton-proton, proton-antiproton and electron-positron colliders in the context of brane world models with low-scale quantum gravity [25]. The inclusion of the case of tidal charged BHs in BlackMax is a complex problem. The available parameter space will be inferred from the bounds coming from the study of BHs produced in very dense environments. If they decay inside the detectors what are the unique features which will allow us to pinpoint such an event? If their lifetimes are long and they escape from the detectors, what exactly can help us identify such events? Can they be identified as events for which there are large amounts of missing energy? How will these events look like? Will they be charged and what will be the mass to charge ratio to make their tracks distinguishable? As we will become more familiar with BlackMax, we will also contribute to testing, enhancing and updating the software. The contribution to the BlackMax project will not be limited to the directions stated above. In scientific research new ideas are developed continuously and some of them will lead to new enhancements and additions to the software. A collaboration with Prof. Dr. Dejan Stojkovic will be very beneficial for the realization of this research project due to his well known expertise in, but not limited to BHs physics; and also as one of the authors of BlackMax. The proposed time line is as follows:

- Analysis of the possible signatures for the case of long lived BHs (3 months);
- Inclusion of the tidal charged BHs case into BlackMax (2 months);
- Numerical simulations and enhancing the software (4 months);

C) Microscopic BHs might be produced in high energy particle collisions with the center of mass energies above the fundamental scale of gravity and induce extensive air showers potentially detectable by a large surface detector like Pierre Auger Observatory. We plan to investigate two possible observation scenarios. First it has been found that BH interactions generate different air showers from Standard Model interactions [26] as BH air showers tend to rise faster and have larger muon content producing a hadronic air shower which occurs at a much greater depth in the atmosphere than the Standard Model one. Second, simulations (Gora, D. et al, ICRC 2009) showed that the expected event rate calculated for up-going and down-going showers induced by microscopic BHs show a significant deviation of the expected rate compared to the rate by SM predictions, making the non observation of up-going neutrinos by the Pierre Auger Observatory in conjunction with a high rate of down-going neutrino-induced showers, a strong indication of physics beyond the Standard Model. These scenarios will be verified by using publicly available software like PYTHIA (http://home.thep.lu.se/~torbjorn/Pythia.html), a program for the generation of high-energy physics events, which will be used as input for the air shower simulation software AIRES (http://www.fisica.unlp.edu.ar/auger/aires/) to create shower profiles and footprints, which can then be analyzed with Auger software framework, e.g. Offline. Using this we can make prediction on the detection limits, and providing Pierre Auger Observatory will achieve enough statistics, even make a possible detection. The proposed time line is as follows:

- Analysis of the possible BH signatures which can be observed in air showers (3 months);
- Numerical simulations used to create shower profiles and footprints (2 months);
- Predictions on the detection limits (2 months);
- Data analysis (3 months).

D) We propose to further investigate the anomalies observed in the experimental neutrino data. A careful analysis of all neutrino data suggests some exotic physics taking place in the neutrino sector. The different resonance energies in the neutrino and antineutrino channels make one think about the possibility of neutrino-antineutrino oscillations. This only becomes possible if CPT is not an exact symmetry of nature. Several things will be investigated in this context. We will investigate which terms in the most general form of the neutrino oscillations Hamiltonian [20] modify the neutrino dispersion relations in a way which is consistent with the experimental data. It is also interesting to calculate if neutrino-antineutrino oscillations generated via breaking the CPT invariance can lead to lepton number violation starting from the assumption that neutrinos are Dirac particles. Under the same initial assumptions we will calculate the implications that this possibility has on neutrinoless double beta decay. In the standard scenario, neutrinoless double beta decay is only possible if neutrinos are Majorana particles. If neutrino-antineutrino oscillations are realized in nature, neutrinoless double beta decay might be possible even with Dirac neutrinos.

Close contact also exists with the MiniBooNE collaboration which will also be a part of the proposed MicroBooNE experiment. The latter, was proposed in order to check the MiniBooNE findings. If approved it will have a much higher resolution in the low energy part of the spectrum, more exactly at the energies where MiniBooNE saw an excess when working in neutrino mode. The concrete proposed time line is as follows:

- Analysis of the spectrum of resonances which occur starting from a generalized form of the neutrino oscillations Hamiltonian (3 months);

- Evaluate the possibility of lepton number violation starting from Dirac neutrinos and neutrino-antineutrino oscillations (3 months);

- Put bounds on neutrinoless double beta decay (or use existing bounds on neutrinoless double beta decay to put bounds on the CPT- and Lorentz- violating parameters) (2 months).

In the near future there will be a large amount of data in the neutrino field. This happens simultaneously to, and maybe even earlier than the data from the LHC experiments. Neutrino physics has entered the precision regime which makes it possible to look for exotic scenarios like CPT violation. The energy at the LHC will also reach the regime which will allow to check for BHs formation and test extra dimensional theories. In the mean time the Pierre Auger Observatory already accumulated a large amount of data in this regime and perhaps a careful analysis is all that is necessary to elucidate this puzzle.

C4. *Impact, relevance, applications*.

When accepted, the proposal will have impact from several perspectives.

Clarifying the existence or nonexistence of BHs in the TeV range has consequences on many physics models. If the existence of TeV BHs is confirmed, this will be a clear statement about the scale of gravity being low, which can only happen in brane world models/extra dimensional theories. This would also be a confirmation of string theory, which would be a very big step for the scientific community. Until now only BHs in the ADD scenario were looked for at the LHC. For completeness, it is also important to see what happens in the RS brane world model. Finding the signatures of long lived BHs at the LHC or in the data accumulated by the Pierre Auger Observatory would validate the RS scenario. Assuming that the extra dimensional theories are true, this is also one way to tell the difference between the two models. In the ADD scenario BHs are created and they decay instantaneously, while in the RS scenario they can be long lived.

Solving the LSND/MiniBooNE puzzle is an important issue in neutrino physics. As stated before there is no mechanism that we know of which can accommodate all the data in a 3 neutrino framework. Confirming the existence of more than 3 neutrinos or modifications of the neutrino dispersion relations would have very strong consequences on how we analyze the whole neutrino data and would not be limited to that. If sterile neutrinos exist, they also contribute to the budget of dark matter. The existence of sterile neutrinos or modifications of the neutrino dispersion relations open many new questions in neutrino physics and beyond.

The implementation of this proposal at the Institute for Space Sciences would facilitate new collaborations both for the institute and for the project leader. Strong collaborations in the area of BHs physics exist with Prof. Dr. Benjamin Harms (University of Alabama) and Prof. Dr. Roberto Casadio (University of Bologna & INFN). More recently a new collaboration in the area of

Quantum Gravity was initiated with Dr. Piero Nicolini (Frankfurt University). To implement the tidal charged BHs case into BlackMax, a new collaboration with Prof. Dr. Dejan Stojkovic (SUNY Buffalo) is underway. In the area of neutrino physics I have collaborations with Prof. Dr. Heinrich Päs and Mr. Sebastian Hollenberg (Technische Universität Dortmund) and Prof. Dr. Thomas Weiler (Vanderbilt University).

I was also invited to be part of the theory group for the recently proposed experiment MicroBooNE which is going to take place at Fermilab. Also in the area of neutrino physics collaborations will be possible with the ANTARES and KM3NeT neutrino telescopes via Dr. Vlad Popa (Institute for Space Sciences) who is a member of both experiments. The Institute for Space Sciences has collaborations with the LHC and the Pierre Auger Observatory, which will facilitate the successful realization of several of the proposed research objectives. Collaborations with the Pierre Auger Observatory can also be established via Dr. Peter Biermann who is an Adjunct Professor at the University of Alabama. Dr. Vlad Popa is also a member of the MoEDAL experiment hoasted at CERN and is designed to search for exotic physics beyond the Standard Model.

To summarize, the realization of the proposed research objectives will have a considerable scientific impact in the respective research areas. The implementation of the project at the Institute for Space Sciences will be extremely profitable both for the young research team and for the Institute by opening a gateway towards many new research projects and collaborations.

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