Scientific report 2013

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I joined the ICTP-SAIFR a couple of months ago; my contract started on October 1st 2013.

• Journal Club on Particle Phenomenology

On November 14th I led a discussion in the Journal Club on particle phenomenology about a recent paper on 'Dark matter production from Goldstone boson interactions and implications for direct searches and dark radiation'.

• Astrophysics & Cosmology Journal Club (AC♮JC)

Together with Saeed Mirshekari we started a Journal Club devoted to subjects related to cosmology and astrophysics. It has been scheduled for every two weeks on Mondays 11:00 am in the room #3 of the ICTP-SAIFR. Each AC♮JC session has two parts: First, we have a free discussion on a few recent papers suggested by the audience; then we focus on a paper that is presented in more details. Prof. Rogerio Rosenfeld (IFT-UNESP), Dr. Arman Esmaili Taklimi (Unicamp) and Prof. Gary Steigman (Ohio State University) have discussed papers in the AC♮JC. The Journal Club has been well received and has been attended by people from both the UNESP (ICTP + IFT) and the USP (IAG + IF). It will continue in the next semester.

• Publication

Just after joining the ICTP-SAIFR, an article that I wrote in collaboration with Stefano Colluci (Uni Bonn, Germany), François-Xavier Josse-Michaux (CFTP, Portugal), Juan Racker (IFIC, Spain) and Lorenzo Ubaldi (Uni Bonn, Germany) got accepted for publication in JCAP: *JCAP 1310 (2013) 035*. The title is: 'On baryogenesis from dark matter annihilation'. In that paper we study in detail the conditions to generate the baryon asymmetry of the universe from the annihilation of dark matter (DM). This scenario requires a low energy mechanism for thermal baryogenesis, hence we first discuss some of these mechanisms together with the specific constraints due to the connection with the DM sector. Then we show that, contrary to what stated in previous studies, it is possible to generate the cosmological asymmetry without adding a light sterile dark sector, both in models with violation and with conservation of $B - L$. In addition, one of the models we propose yields some connection to neutrino masses.

• **Research plans for the year 2014**

Currently with Raghuveer Garani (Uni Bonn, Germany), Jaime Forero-Romero (Uni Andes, Colombia) and Sergio Palomares-Ruiz (IFIC, Spain) we are studying the systematic uncertainties induced by halo triaxiality in WIMP DM searches. In order to quantify the interaction rates in direct and indirect detection experiments, one has to have under control not only the particle physics properties of the DM particle (mass, cross sections and annihilation/decay channels) but also the astrophysical properties. In particular one has to know the local DM relic density ρ_0 for direct detection and the whole shape of the DM halo for indirect detection. Let me note that what enters in the flux for indirect detection is a J factor that corresponds to the integral of the DM halo profile along the line of sight. The most promising method to learn about the functional forms of the density profiles is through sophisticated N-body simulations of structure formation in the universe. Important halo properties such as DM density radial profile, halo mass concentration and halo shapes can be discerned from this technique. In general, N-body simulations predict that the DM mass distribution in the halo to be aspherical and favor triaxial shapes. The impact of the triaxial of the halo on local observables such as the DM local density, the velocity dispersion and the J factors can be significantly large and induces systematic uncertainties. Using the DM-only Bolshoi simulation we are discussing the impact of halo triaxiality in the determination of DM event rates. We are noticing that there can be large deviations of ρ_0 and J factor from that of the spherically averaged values for triaxial halos. These deviations can be very large for ρ_0 and about 20% for J, for typical triaxial halos.

In recent years, a possible connection between the abundances of baryons and DM has been explored. Even if so far most of the studies have been in the context of the so-called asymmetric DM, a very different mechanism, dubbed 'WIMPy baryogenesis', has been recently proposed to relate the baryon asymmetry to (symmetric) DM annihilation. In both cases the DM candidate is a usual WIMP, thermally produced, with mass and interactions at the weak scale. However, there are alternate mechanisms of DM genesis involving Feebly Interacting Massive Particles (FIMPs), interacting so feeble with the thermal bath that they never attain thermal equilibrium. With some collaborators we already have studied realizations of the WIMPy baryogenesis and we are pursuing the research now focusing in the possibilities of generating simultaneously the observed baryon asymmetry of the universe and the measured FIMP DM relic abundance.

I also plan to start collaborations with the local people (UNESP and USP), in particular with Prof. Rogerio Rosenfeld, Prof. Eduardo Pontón and Prof. Gary Steigman.

Research Report 2013

Gero von Gersdorff

Introduction

After completion of the first run of the LHC, we have started to probe physics responsible for electroweak symmetry breaking. The electroweak scale is many orders of magnitude lower than the Planck scale or the scale of a grand unified theory (GUT). For this reason, it is widely expected that new physics has to be present somewhere above the mass scale of the W and Z bosons. On the other hand, precision measurements at LEP have shown that the SM accounts extremely well for all physics up to energies at least ten times the W mass, providing strict bounds and constraints, and setting the scale of new physics around the Teraelectronvolt (TeV). It is thus a very challenging task to build actual models which explain the low scale of EWSB without the necessity of severe fine tuning of parameters.

Last year, the ATLAS and CMS experiments have announced the discovery of a new boson of mass ~ 125 GeV with properties consistent with the SM Higgs boson. The nature of the Higgs sector gives an excellent window to new physics, as almost all scenarios beyond the SM predict somewhat different Higgs couplings than the SM.

Moreover, the SM is extremely successful in explaining why flavour or family symmetry is respected to high degree in nature: given the particle content of the SM, the only gauge invariant operators that can generate dangerous flavour changing neutral currents (FCNC's) have dimension greater than four, and are hence irrelevant, i.e., suppressed by the Planck scale. There is no reason to believe that physics beyond the SM respects flavour symmetry. Nonetheless, numerous measurements in meson and lepton physics show no such transitions. Without a suppression mechanism, the scale of new physics has to be as high as 10^5 TeV in order to adequately suppress FCNC's. This is in stark contrast to the expectation that new physics should appear at the TeV-scale to explain EWSB in a natural way. Rather similar considerations apply for the symmetry that exchanges particles with antiparticles (CP). It is therefore absolutely necessary for any theory of new physics to include a mechanism which suppresses FCNC's and CP violation.

Research in 2013

I joined ICTP-SAIFR in April 2013 under a FAPESP fellowship. In that period, I have worked on the following projects.

The Higgs Boson as a Window to New Physics [1].

The SM predicts the couplings for all its particles to the Higgs boson. On the other hand, the LHC will be able to measure some of these couplings to a level of $\sim 5\%$ accuracy, which already allows us to put some limits on New Physics scenarios.

At present, the measured Higgs properties are consistent with the SM. In the diphoton channel there are however intriguing deviations at the 2σ level which might well be due to statistical fluctuations or unknown systematics, or they might be the first sign of some New Physics coupling to the Higgs

Given the trend of the data to coincide with the SM predictions, it seems justified to consider the hypothesis that New Physics states, if present, have masses considerably larger than the electroweak scale. For their impact on measurements at the Higgs mass pole it is then sufficient to integrate out these states. The resulting theory contains only SM particles and interactions, supplemented by a set of operators of dimension greater than four whose coefficients can be constrained. The large mass of the new states allows one to truncate the expansion in the dimension of the operators and only up to dimenension six operators need ot be considered. The effect of many higher dimensional operators (HDO's) have been considered in relation with e.g. FCNC's and electroweak precision data, and some of the coefficients are tightly constrained. Building on the success of this approach, my collborators and I have performed a corresponding analysis for the Higgs properties [1].

The parametrization of New Physics by HDOs has several advantages over the conventional approach, in which each Higgs coupling is considered as a separate parameter, in particular it has fewer parameters and thus allows a correlation between the different couplings that in other approaches are unrelated.

We have used Baysean inference which allowed us to easily marginalize over parts of the parameters space and to quote Bayesean Credible Intervals for all relevant operator coefficients. We have found that the HDO coefficients are already quite constrained, but still allow for certain deviations, in particular in the top Yukawa coupling as well as in the coupling of the Higgs to a photon and a Z boson.

Supersymmetric Models of Flavour [2].

Supersymmetry still remains one of the best motivated scenarios for a natural electroweak scale. Given the so far negative outcome of direct searches at the LHC, a certain tension has arisen, as heavy superpartners require more fine tuning for successful EW breaking. However, as has been realized a long time ago, only the top squarks and gluinos need to be light to avoid this situation, and one can have a perfectly natural scenario with heavier first two generation squarks. This scenario, in which only the states necessary for naturalness remain light, has been dubbed Natural Supersymmetry, and so far is not excluded by LHC limits (which mainly apply to the first two generation squarks.

FCNCs and CP violation are generically arising in all supersymmetric extensions of the SM in which all or part of supersymmetry breaking is mediated by gravity, as the soft masses for the superpartners have no reason to be flavour-blind. It has been suggested that there might be a link to the spectrum of Natural Supersymmetry, as both from flavour physics and from direct searches the limits are the strongest for the first two generation superpartners. However, as bounds on flavour have improved, it has also become clear that a simple decoupling of the flavour problem (by multi-TeV first two generation squark masses) is not possible and some other flavour protection must be simultaneously present. One (obvious) such mechanism is a symmetry that suppresses mixing of squarks of different generations.

We have proposed a model [2] based on a family symmetry $G \times U(1)$, where G is a discrete nonabelian subgroup of $SU(2)$, with both F-term and (abelian) D-term supersymmetry breaking. A good fit to the fermion masses and mixing is obtained with the same $U(1)$ charges for the left- and right- handed quarks of the first two families and the right-handed bottom quark, and with zero charge for the left-handed top-bottom doublet and the the right handed top. The model shows an interesting indirect correlation between the correct prediction for the V_{ub}/V_{cb} ratio and large right-handed rotations in the (s, b) sector, required to diagonalise the Yukawa matrix. For the squarks, one obtains almost degenerate first two generations. The main source of the FCNC and CP violation effects is the splitting between the first two families and the right-handed sbottom determined by the relative size of F-term and D-term supersymmetry breaking. The presence of the large right-handed rotation implies that the bounds on the masses of the first two families of squarks and the right handed sbottom are in a few to a few tens TeV range. The picture that emerges is light stops and left handed sbottom and much heavier other squarks.

Models of Flavour in Warped Geometries [3].

Warped extra dimensions, or Randall Sundrum (RS) models, are a very interesting alternative explanation for a natural electroweak scale. Moreover, they incorporate an explanation of the fermion mass hierarchy observed in nature, without relying on very small Yukawa couplings. Instead, suppression factors appear naturally as exponentially suppressed wavefunction overlap integrals. The very same suppression factors also tame the dangerous FCNCs.

In recent paper [3] I have reviewed the bounds on these models arising from both hadronic and leptonic physics. The strongest bound originate from neutral meson mixing and from $\mu \to e\gamma$ rare decays, both pointing to a Kaluza Klein scale in the range ~ 20 TeV and above. Baring fine-tuned scenarios, the RS flavour paradigm needs to be supplemented with additional FCNC suppression mechanism such as symmetries or a modified geometry.

Anomalous Gauge Couplings [4].

Yet another set of SM couplings that can be studied at the LHC at high precision are the gauge-boson self interactions. In particular, neutral quartic gauge boson self interactions are highly suppressed in the SM and are hence a particulary interesting window to New Physics. Such effective interactions are mediated only by dimension-8 operators, and thus to probe them one needs energies much larger than the EW scale, attainable at the LHC.

In a recent paper [4] we have studied the generation of such couplings in a series of well-motivated extensions of the SM, such as composite Higgs models and models with warped extra dimensions. We derived the general perturbative contributions to the pure field-strength operators from spin 0, $\frac{1}{2}$, 1 resonances by means of the heat kernel method. In the composite Higgs framework, we derived the pattern of expected deviations from typical

$SO(N)$ embeddings of the light composite top partner. We then studied a generic warped extra dimension framework with AdS_5 background, recasting in few parameters the features of models relevant for anomalous gauge couplings. We also presented a detailed study of the latest bounds from electroweak and Higgs precision observables, with and without brane kinetic terms. We have found that, for vanishing brane kinetic terms, EW precision observables require KK masses of at least 6 TeV, even in models where custodial symmetry suppresses the T parameter. We also presented a detailed study of these constraints in the presence of brane kinetic terms. While this allows one to relax the constraints from EW precision tests, anomalous gauge couplings are unsuppressed in this region of parameter space, and can provide dominant constraints.

Conferences and Seminars

In the period April-December 2013 I have presented my work at the following conferences and seminars.

- May 2013, University of Mainz, Germany
- June 2013, GGI Institute, Florence, Italy
- September 2013, lecturer at BUSSTEPP, University of Sussex, Brighton, UK
- September 2013, WIN 2013 Conference, Natal
- September 2013, IIP, University Rio Grande do Norte, Natal
- December 2013, HEP 2013 Conference, Valparaiso, Chile

Present and Future Research Lines

Anomalous Gauge Couplings

Together with experimentalists from Atlas we are working on a study about 4-photon self interactions. In particular we aim at presenting a "simplified model" analysis that is easy to map onto particular New-Physics models, and a study of the sensitivity of the future Atlas Forward Proton detector to these couplings.

Anomalous Top Couplings

Top anomalous couplings are a further window to new physics. In the HDO framework there exist many operators that can modify couplings, and a comprehensive study of the correlated effects from other sectors (EW precision tests, Higgs physics) would be interesting. Moreover, LHC will also provide direct measurements of the top-couplings to W and Z bosons, albeit with moderate precision. Under the hypothesis of heavy New Physics, it would be very interesting to know how much additional discriminatory power these measurements have, or, put differently, whether other precision meaurements allow sufficient room for the HDO coefficients to describe significant deivations in these couplings.

Operator Mixing

Given that the New Physics scale is typically in the TeV to multi-TeV range, there can be significant operator mixing in RG flow to the EW scale. The anomalous dimension matrix has only been partially computed, and it would be interesting to compute it in full generality. A natural framework to do so are covariant background methods (heat kernel expansion), which allows one to maintain full gauge covariance, which is very useful when studying local operators in the unbroken phase.

Strongly Coupled Radion/Dilaton

The radion/dilaton is a particle common in extra-dimensional extensions of the SM, or in their strongly coupled dual descriptions in 4 dimensions. The dilaton is a Goldstone boson of spontaneously broken scale invariance, and receives its mass from an explicit deformation of the conformal field theory. Traditionally, one assumes that this deformation remains small at the scale of spontaneous conformal breaking, resulting in a light and weakly coupled dilaton. However, this dominance of spontaneous over explicit breaking has been shown to exhibit a hidden fine-tuning. More natural models would have a much heavier and much more strongly coupled dilaton. It would be very interesting to study out the phenomenology of such a scenario, which has so far not received any attention.

References

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DATA ANALYSIS OF GRAVITATIONAL WAVES AND ALTERNATIVE THEORIES OF GRAVITY

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FAPESP Postdoctoral Research Fellow

December 6, 2013

Abstract

This is a short report on my research activities as a FAPESP Postdoctoral Research Fellow at ICTP-SAIFR since September 2013. In this document, I briefly review my current research projects and mention a few words about my future research plans. Some preliminary results are also presented.

1 Gravitational Waves Data Analysis

1.1 Introduction

The anticipated completion of upgrades to kilometer-scale, laser interferometric gravitational-wave (GW) observatories in the U.S. (LIGO) and Europe (VIRGO) and their resumption of operations in the 2015 time frame hold the promise to open a new astronomical window in the high-frequency GW band. Since GW signals are extremely weak compared to the background noise, an accurate data analysis is crucial to extract the buried GW signals from the noisy data. An accurate data analysis provide a mechanism to study the physical properties of the astronomical GW sources.

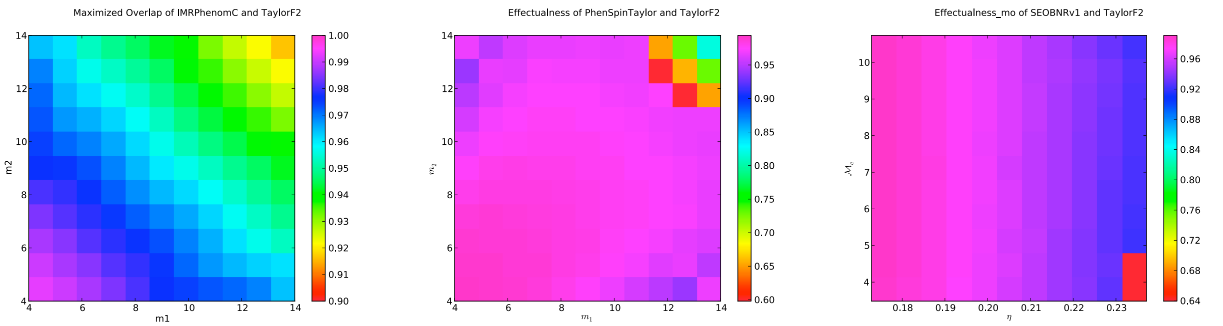
1.2 Testing the Consistency of the Waveforms

We plan to review the consistency of various waveforms as an important task in the data analysis of GWs. We use LAL (LSC Algorithm Library) to calculate (a) faithfulness, (b) effectualness, and (c) parameter-bias of various waveform approximants (see [1, 2] for the definition of each case). Figure 1 shows a few examples of the preliminary results for non-spinning waveform approximants. You can find a detailed report on this work and a more complete list of result plots at http://www.physics.wustl.edu/smirshekari/LIGOreport2013.pdf.

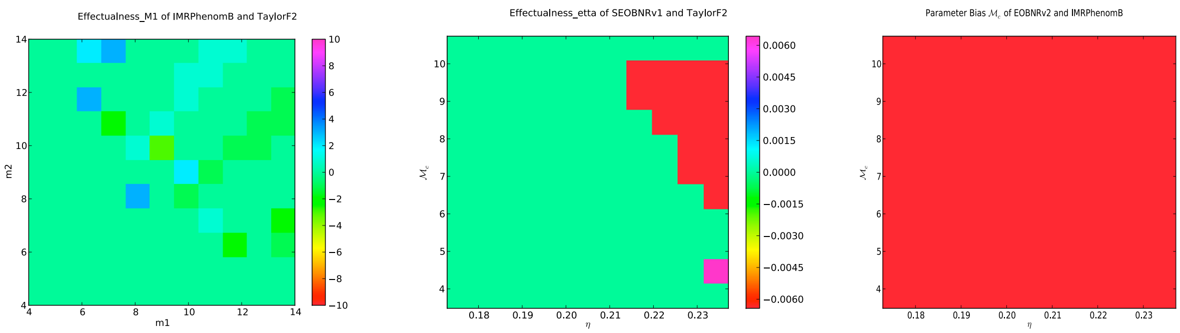
There are a few issues in the results that have to be fully understood. We will continue to develop the code and perform some checks to confirm the final results. We have to increase the level of accuracy in the calculation of faithfulness and effectualness (i.e. the resolution of the plots in Figure 1) wherever it is needed and eventually run the code on one of the LIGO computer clusters for the expensive computations.

1.3 Contribution to the Waveform Data Analysis Group of LSC

ICTP-SAIFR joint LIGO Scientific Collaboration (LSC) in October 2013. The members include Riccardo Sturani and Saeed Mirshekari. The research activities in this sector are under the Compact Binary Coalescence (CBC) group and the Waveform subgroup of LSC. Our group participates actively in the weekly CBC and the biweekly Waveform teleconferences. Recently, I gave a short presentation in the waveform teleconference (2 December, 2013) on the preliminary results of my work. To interact with several colleagues and collaborators in LSC including Evan Ochsner and Jolien Creighton, I will be visiting the gravity group of the University of Wisconsin-Milwaukee from December 2013 to February 2014.



(a) Faithfulness in m_1-m_2 plane for IMRPhenomC-TaylorF2 (b) Effectualness in m_1-m_2 plane for PhenSpinTaylor-TaylorF2 (c) Effectualness in η-$\mathcal{M}_c$ plane for SEOBNRv1-TaylorF2



(d) parameter-bias of m_1 in m_1-m_2 for IMRPhenomB-TaylorF2 (e) parameter-bias of η in η-$\mathcal{M}_c$ plane for SEOBNRv1-TaylorF2 (f) No parameter-bias for $\mathcal{M}_c$ in η-$\mathcal{M}_c$ plane (Red=0)

Figure 1. Faithfulness, effectualness, and parameter-bias for various waveforms in m_1-m_2 and η-$\mathcal{M}_c$ planes. Each panel presents a sample result for a specific combination of the waveforms. Higher resolution is needed to distinguish parameter-bias for $\mathcal{M}_c$ in η-$\mathcal{M}_c$ plane (the panel in bottom-right). A 180° rotation around the diagonal axis of $m_1 = m_2$ converts the parameter-bias of m_1 to its correspondence of m_2 and vice versa.

2 Alternative Theories of Gravity: Multiple-Scalar Theories

A broad class of classical relativistic field theories of gravity containing N finite-range scalar fields and a metric tensor, and satisfying the Weak Equivalence Principle, can be constructed in both the Jordan and Einstein frames in a target-space-covariant manner (the weak-field limit of tensor-multi-scalar theories has been worked out in [3]). The field equations can be cast into both hyperbolic form suitable for numerical integration, and relaxed harmonic form suitable for Post-Minkowskian (PM) and Post-Newtonian (PN) expansions. We have successfully checked the consistency of our results for the case of a single scalar field ($N = 1$) with the previous results [4].

A tensor-bi-scalar theory of gravity with spherical target-space geometry is explicitly constructed. This theory passes solar-system and binary-pulsar tests, and contains an unconstrained parameter, namely, the target-space curvature, which enters at higher Post-Newtonian orders into the waveform emitted by a compact-binary-inspiral. Potential bounds on this parameter coming from future gravitational wave observations can be made.

This work is in collaboration with Michael Horbatsch, Emanuele Berti, and Hector O. Silva from University of Mississippi. Riccardo Sturani from ICTP-SAIFR also might be interested to get involved in this project. This project has been started in summer 2013 when I was still in University of Florida and we continued to work on it also after I moved to Saõ Paulo. The gravity group of the University of Mississippi will be hosting a workshop on Testing General Relativity with Astrophysical Observations at 6–10 January, 2014 that I will be attending. I will meet many of my colleagues there and will have a chance to have a closer collaboration on this work.

3 Broader Impact

I delivered a seminar talk at ICTP-SAIFR about my PhD work [5] on “Gravitational Waves and Inspiralling Compact Binaries in Alternative Theories of Gravity” (29 October, 2013). In this talk, I also briefly explained the ongoing research and future plans in the GWs Data Analysis group at ICTP-SAIFR led by Riccardo Sturani under LSC.

With Nicolás Bernal, another FAPESP fellow at ICTP-SAIFR, we have started and organized a biweekly Journal Club at IFT-UNESP on Astrophysics and Cosmology (AC/JC). The participants are faculties, post-docs, and graduate students in the field of high energy physics from IFT-UNESP, ICTP-SAIFR, IAG-USP, and IF-USP. A website has been developed at https://sites.google.com/site/ictpsaifrjc for a better organization and communication.

Working closely with Sturani, I have learned new topics and developed my skills in Data Analysis of Gravitational Waves. I also gained valuable experiences on working with LAL which is a library of routines (in Python and C++ languages) to perform numerical calculations of gravitational wave data analysis.

I will continue to maintain my website at http://physics.wustl.edu/smirshekari (eventually to be transferred to the ICTP domain) with freely available information related to my research, including links to published papers, links to the notes and presentations, and explanatory information on ongoing research topics.

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Service and Outreach

Referee for JHEP.

Referee for Int. J. Mod. Phys. A.

Invited talks, Presentations and Workshops in 2013

Invited talk, ICTP South American Institute for Fundamental Research, São Paulo, Brazil, February 4, 2013.

Invited talk, Interdisciplinary Center for Theoretical Study, USTC, Hefei, China, April 3, 2013.

Participant in *"School on Non-Perturbative QCD"*, São Paulo, Brazil, May 27-June 7, 2013.

Invited talk, USP Universidade de São Paulo, São Paulo, Brazil, June 18, 2013.

Participant in *"Simons Summer Workshop 2013"*, Simons Center for Geometry and Physics, USA, July 22-26, 2013.

Participant in *"School on Approaches to Quantum Gravity"*, São Paulo, Brazil, September 2-9, 2013.

Participant in *"School on Fundamental Astrophysics"*, São Paulo, Brazil, October 7-18, 2013.

Participant in *"Rosly minicourse on twistor theory"*, São Paulo, Brazil, October 8-November 15, 2013.

Participant in *"Program on Amplitudes and Correlation Functions"*, São Paulo, Brazil, October 20-December 20, 2013.

Participant in *"Workshop on Higher-Spin and Higher-Curvature Gravity"*, São Paulo, November 4-7, 2013.

Publications in 2013

G. Jorjadze, C. Kalousios and Z. Kepuladze, *"Quantization of $AdS \times S$ particle in static gauge"*, Class. Quant. Grav. **30**, 025015 (2013). arXiv:1208.3833 [hep-th].

J. R. David, C. Kalousios and A. Sadhukhan, *"Generating string solutions in BTZ"*, JHEP **1302**, 013 (2013). arXiv:1211.5382 [hep-th].

Published work

Quantization of AdS×S particle in static gauge

In this paper we quantized the AdS×S particle dynamics in static gauge. We used the quantization scheme of [1] based on a covariant construction of the energy square operator in the coordinate representation, where the wave functions depend only on spatial coordinates. Let us first outline the scheme, which we present here in a slightly modified form.

Particle dynamics in a spacetime with coordinates x^μ, $\mu = (0, 1, ..., \mathcal{N})$ and a metric tensor $g_{\mu\nu}(x)$ can be described by the following action in the first order formalism

$$S = \int d\tau \Big(p_\mu \, \dot{x}^\mu - \frac{\lambda}{2} \left(g^{\mu\nu} p_\mu p_\nu + \mathcal{M}^2 \right) \Big) \; . \tag{1}$$

Here $\mathcal{M}$ is the particle mass, λ is a Lagrange multiplier and its variation provides the mass-shell condition

$$g^{\mu\nu} p_\mu p_\nu + \mathcal{M}^2 = 0 \; . \tag{2}$$

Using the Faddeev-Jackiw reduction [2] in the gauge

$$x^0 + p_0 \tau = 0 \; , \tag{3}$$

from (1) we get an ordinary Hamiltonian system[1]

$$S = \int d\tau \Big(p_n \, \dot{x}^n - \frac{1}{2} \, p_0^2 \Big) \; , \tag{4}$$

where p_0^2, as a function of the spatial coordinates and momenta (x^n, p_n) $(n = 1, ..., \mathcal{N})$, is obtained from the constraint (2) and the gauge fixing condition (3).

Notice that here we have modified the form of the standard static gauge $x^0 = \tau$ used in [1]. However, this modification does not change the quantization scheme and it appears more convenient for a Hamiltonian treatment of (4) in a static spacetime, as well as for the generalization to string theory [3].

A static spacetime metric tensor can be represented in the form

$$g_{\mu\nu} = \begin{pmatrix} g_{00} & 0 \\ 0 & g_{mn} \end{pmatrix} \; , \tag{5}$$

where g_{00} and g_{mn} are functions only of the spatial coordinates x^n. In this case the particle energy $E(p, x) = -p_0 > 0$ is conserved and from (2) follows that

$$E^2 = \Lambda(x) \, g^{mn}(x) \; p_m p_n + \mathcal{M}^2 \, \Lambda(x) \; , \tag{6}$$

with $\Lambda(x) := -g_{00}(x) > 0$.

Thus, the Hamiltonian in (4) corresponds to a motion of a particle in the potential field $V(x) = \frac{1}{2} \mathcal{M}^2 \, \Lambda(x)$ and in a curved background with metric tensor

$$h_{mn}(x) = \frac{1}{\Lambda(x)} \; g_{mn}(x) \; . \tag{7}$$

It is natural to quantize this system in the coordinate representation, where the wave functions $\psi(x)$ form a Hilbert space with covariant scalar product

$$\langle \psi_2 | \psi_1 \rangle = \int d^{\mathcal{N}} x \, \sqrt{h(x)} \; \psi_2^*(x) \, \psi_1(x) \; , \qquad h(x) := \det h_{mn}(x) \; . \tag{8}$$

[1] We neglect the total derivative term $-\frac{\mathrm{d}}{\mathrm{d}\tau} \left(\frac{1}{2} \, p_0^2 \tau \right)$.

On the basis of DeWitt's construction for quadratic in momenta operators [4], it was argued in [1] that the energy square operator is given by

$$E^2 = -\Delta_h + \frac{\mathcal{N}-1}{4\mathcal{N}}\,\mathcal{R}_h(x) + \mathcal{M}^2\,\Lambda(x)\ . \tag{9}$$

Here Δ_h is the covariant Laplace-Beltrami operator for the metric tensor h_{mn} and $\mathcal{R}_h(x)$ denotes the corresponding scalar curvature. The solution of the eigenvalue problem for (9) then provides the energy operator in diagonal form.

The coefficient in front of the scalar curvature term has been a subject of discussions during decades (see [5] and references therein). Therefore it is useful to comment on the value of this coefficient, $\frac{\mathcal{N}-1}{4\mathcal{N}}$, chosen in (9).

For the particle dynamics in $\mathrm{AdS}_{\mathcal{N}+1}$ this coefficient was calculated in [1] from the commutation relations of the symmetry generators. In this case $\mathcal{R}_h(x)$ corresponds to the curvature of a semi-sphere and, therefore, it is constant. The obtained constant shift in the energy square operator provides its spectrum in the form $(E_0+n)^2$, with fixed E_0 and a non-negative integer n, that leads to the correct energy spectrum for the AdS particle.

For a generic $\mathcal{N}+1$ dimensional static spacetime the same value of the coefficient $\frac{\mathcal{N}-1}{4\mathcal{N}}$ follows from the equivalence between the static gauge quantization and the covariant quantization based on the Klein-Gordon type equation.

The covariant quantization is a more conventional approach to the particle dynamics in AdS backgrounds [6, 7]. The general case with arbitrary dimensions and radii in this approach was analyzed in [8] from the perspective of scalar field propagators (see also [9]).

An interesting alternative quantization scheme based on the twistor and BRST formalisms was proposed in [10] for a massive bosonic particle in AdS_5. The obtained twistor construction was related to the oscillator construction of [11].

The quantization of a superparticle in the $\mathrm{AdS}_5\times\mathrm{S}^5$ background was done in [12], using the lightcone gauge and the technique developed in [13] (see also [14], which is based on a different lightcone type gauge).

The dynamics of a massive bosonic particle in $\mathrm{AdS}_5\times\mathrm{S}^5$ was considered in [15]. The authors used gauge invariant approach[2] and Dirac brackets formalism. The obtained results were applied for the analysis of string energy spectrum at large coupling in the context of the AdS/CFT correspondence.

The main motivation of most of papers on particles dynamics in the AdS spaces is to develop useful methods for the quantization of strings in these backgrounds.

Our motivation is the same and in this paper we aim to apply the static gauge quantization to $\mathrm{AdS}_{N+1}\times\mathrm{S}^M$ particle. AdS_{N+1} will be realized as a hyperbola $X^A\,X_A=-R^2$, with $A=(0',0,1,...,N)$, embedded in $\mathbb{R}^{2,\,N}$ and S^M as a M-dimensional sphere $Y_I\,Y_I=R_S^2$ in $\mathbb{R}^{M+1}$, with $I=(1,...,M+1)$.

Generating String Solutions in BTZ

Classical solutions of strings moving in $AdS_5\times S^5$ backgrounds have played an important role in the AdS/CFT correspondence. Spinning strings in AdS or the sphere have been established as excitations dual to operators with large spins or R-charges respectively [16]. These solutions were crucial in discovering the role of integrability and verifying many of its predictions in the AdS/CFT correspondence, see [17] for a review and a comprehensive list of references. Conversely integrability of strings in AdS was used to generate many new and useful solutions dual to single trace operators as well as Wilson loops in the field theory dual [18, 19, 20, 21].

The $AdS_3\times S^3$ dual pair is another example where the role of integrability is beginning to be investigated [22, 23, 24, 25, 26, 27, 28, 29]. One of the most interesting aspects of this dual pair is that classical string propagation in the background of AdS_3 black holes is integrable unlike the higher dimensional examples [30]. Integrability can be used to classify and generate new classical string solutions in the BTZ background. This in turn will shed light on aspects of black hole physics which can be probed

[2]Other references on gauge invariant quantization of the AdS particle dynamics one can find in [1].

by extended objects. In this paper we apply the dressing method introduced in the AdS/CFT context by [18], to generate and study new solutions of classical strings in the BTZ background.

Trajectories of point like objects described by geodesics are the canonical probes of the causal structure of the black hole. Space like geodesics in black hole backgrounds are used to obtain semi-classical limits of two point correlators in the boundary [31, 32, 33, 34, 35] and to study entanglement entropy of the boundary theory for 3 dimensional backgrounds [36]. Studying the behaviour of extended objects gives access to new phenomena near black hole horizons. For instance general arguments indicate that strings are expected to spread and become tensionless near black hole horizons due to quantum fluctuations [37, 38, 39]. Furthermore minimal surfaces whose boundary are pinned at asymptotic infinity are dual to Wilson/Polyakov loops [40, 41] and are useful probes of the transition from thermal AdS to a black hole in AdS [41, 42] They are also used to evaluate entanglement entropy [36]. See [43] for a nice review and also for some interesting properties of these minimal surfaces. Finally studying spinning strings in the background of black holes in AdS provides clues of the spectrum of the excitations in the dual thermal CFT analogous to the information provided by the spectrum of quasi-normal modes of fields in the black hole background.

The simplest kind of classical string solutions are those which are circular and which wind around the horizon and which then eventually fall into the horizon. Such solutions in the context of the BTZ black holes were studied in [24]. They were classified in terms of the finite gap solutions of the BTZ sigma model. However since the BTZ sigma model is integrable it is possible to apply the dressing method to construct more general classical solutions given a seed solution. In this paper we show how the dressing method developed for the $SU(1,1)$ principal chiral model [20, 21] can be used to generate classical string solutions for the sigma model on BTZ$\times S^1$. One of the by-products of this study is the proof that the dressing method preserves the Virasoro constraints of the seed solution. This method of generating solutions for the sigma model is different from that obtained by the spectral flow method used to obtain long strings in the $SL(2,R)$ WZW model in [44]. The Wess-Zumino term which allowed for the possibility of obtaining new solutions using the spectral flow in the $SL(2,R)$ WZW model is not present in the sigma model on BTZ$\times S^1$ considered in this paper.

We first apply the dressing method on time like geodesics to obtain classical string configurations. We obtain open string configurations which are pinned at the boundary but cross the horizon. The end points of these strings move on time like geodesics which have the same constants of motion as the seed geodesic but different initial condition. After a suitable regularization of the energy E and spin S of these solutions which involves subtracting the energy and spin density of seed geodesic we find that their dispersion relation is by the form

$$E - S = \kappa|\sin\theta|, \tag{10}$$

where κ is a function of the background and θ is the phase of the dressing parameter. Thus the dispersion relation resembles that of the giant magnons found in [45]. We next examine the minimal surfaces obtained by dressing space like geodesics. We show that it is possible to obtain closed strings, they also have a dispersion relation given in (10). These surfaces are pinned at two points on the boundary. These points move on time like trajectories at the boundary.

We finally examine the embedding of the well studied giant gluon solutions of [46, 47] in the BTZ background. These are Euclidean worldsheet solutions. We examine two possible embeddings: In one case these solutions have vanishing energy and spin. The configuration is a spiral which originates from the boundary, contracts and touches the horizon and then expands back to the boundary. In the second solution the embedding solutions has a dispersion relation given by

$$E + S = \kappa \log S. \tag{11}$$

These are spinning spikes which originate from the boundary and touch the horizon.

The organization of the paper is as follows. First we adapt the dressing method developed for the $SU(1,1)$ sigma model to the BTZ background and show that the Virasoro constraints are preserved by the dressing. Then we dress time like geodesics and discuss the properties of the solutions obtained. In section 4 we repeat this analysis for the case of space like geodesics. We then embed the giant gluon solutions in the BTZ background and examine its properties.

Upcoming work

Massless scattering at special kinematics as Jacobi polynomials

Recently a new and elegant formula for the complete tree-level S-matrix of pure Yang-Mills and gravity in arbitrary dimensions has been proposed in [48]. It was later extended to a massless colored cubic scalar theory [49]. The formula was proven in [50]. For a string theory derivation see [51] and [52]

The scattering equations are

$$\sum_{b=1,\, b\neq a}^{n} \frac{k_a \cdot k_b}{\sigma_a - \sigma_b} = 0. \tag{12}$$

According to [48] the tree level partial amplitude of Yang-Mills is given by

$$A_n = \sum_{\{\sigma\}\ \in\ \text{solutions}} \frac{1}{\sigma_{12}\cdots\sigma_{n1}} \frac{\mathrm{Pf}'\Psi(\mathrm{k},\epsilon,\sigma)}{\det'\Phi} \tag{13}$$

and that of gravity as

$$M_n = \sum_{\{\sigma\}\ \in\ \text{solutions}} \frac{\det'\Psi(\mathrm{k},\epsilon,\sigma)}{\det'\Phi}, \tag{14}$$

where $\mathrm{Pf}'\Psi\ =2\ \frac{(-1)^{\mathrm{i+j}}}{\sigma_{\mathrm{i}}-\sigma_{\mathrm{j}}}\mathrm{Pf}(\Psi^{\mathrm{ij}}_{\mathrm{ij}})$, the matrix Ψ^{ij}_{ij} is derived from the matrix Ψ by removing the ith and jth rows and the ith and jth columns with $1 \leq i < j \leq n$, the reduced determinant $\det'\Phi = \frac{|\Phi|^{\mathrm{ijk}}_{\mathrm{pqr}}}{(\sigma_{\mathrm{ij}}\sigma_{\mathrm{jk}}\sigma_{\mathrm{ki}})(\sigma_{\mathrm{pq}}\sigma_{\mathrm{qr}}\sigma_{\mathrm{rp}})}$, where the minor $|\Phi|^{ijk}_{pqr}$ is the determinant of the matrix Φ after removing rows $\{i,j,k\}$ and columns $\{p,q,r\}$, $\det'\Psi = 4\det\Psi^{\mathrm{ij}}_{\mathrm{ij}}/\sigma^2_{\mathrm{ij}}$, the $n\times n$ matrix Φ is defined by

$$\Phi_{ab} = \begin{cases} \dfrac{k_a\cdot k_b}{(\sigma_a-\sigma_b)^2} & a\neq b, \\ -\displaystyle\sum_{c\neq a} \dfrac{k_a\cdot k_c}{(\sigma_a-\sigma_c)^2} & a=b, \end{cases} \tag{15}$$

and finally the $2n \times 2n$ antisymmetric matrix Ψ is defined as

$$\Psi = \begin{pmatrix} A & -C^{\mathrm{T}} \\ C & B \end{pmatrix} \tag{16}$$

with the $n\times n$ matrices $A,\ B,\ C$ defined as

$$A_{ab} = \begin{cases} \dfrac{k_a\cdot k_b}{\sigma_a-\sigma_b} & a\neq b, \\ 0 & a=b, \end{cases} \qquad B_{ab} = \begin{cases} \dfrac{\epsilon_a\cdot \epsilon_b}{\sigma_a-\sigma_b} & a\neq b, \\ 0 & a=b, \end{cases} \tag{17}$$

$$C_{ab} = \begin{cases} \dfrac{\epsilon_a\cdot k_b}{\sigma_a-\sigma_b} & a\neq b, \\ -\displaystyle\sum_{c\neq a} \dfrac{\epsilon_a\cdot k_c}{\sigma_a-\sigma_c} & a=b. \end{cases} \tag{18}$$

We occasionally use the short notation $\sigma_{ab} = \sigma_a - \sigma_b$.

In this work I will focus on a special kinematics that will associate solutions of the scattering equation (12) to roots of Jacobi polynomials. This will let me to explicitly write down expressions of gluon and gravity scattering amplitudes purely in terms of Jacobi polynomials.

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FAPESP SCIENTIFIC REPORT 2013 – TONERO ALBERTO

Research activity

During the year 2013 at ICTP-SAIFR I focused mainly my research activity on two projects. The first one is a phenomenological work in the field of particle physics and has the aim to study the top quark compositeness using the recent collider data. The second one is a theoretical work in quantum field theory and has the aim to give some examples about the computation of the ordinary perturbative effective action using the exact renormalization group equation.

The first project I was involved in, together with some collaborators from SISSA (Trieste), consists in studying top quark compositeness using the most recent measurements coming from LHC and Tevatron.

Whether the top quark is a point-like particle or an extended object is a question that can now be addressed thanks to the large number of them produced at the LHC and the Tevatron. If the top quark is a composite state made out of some constituents, its interaction with the gauge bosons will be modified. The most direct approach is to look into what effect a finite extension of the top quark has on its interaction with the gluon. In analogy with the study of the electromagnetic structure of nucleons, it is possible to parametrize effects of compositeness introducing two independent form factors modifying the vertex between the top quark and the gluon. These form factors can be used to obtain information about the radius and the anomalous magnetic moment of the top quark, in complete analogy with the nucleon case.

Form factors are just a way of organizing the perturbative expansion. An alternative and perhaps better approach is effective field theory. In this study we introduced the leading effective operators that contribute to the radius and anomalous magnetic moment of the top quark and study their effect on the cross section for top-antitop production at the Tevatron and the LHC. The advantage of the effective theory approach is in the book-keeping because higher powers of the anomalous couplings enter suppressed by the higher dimension of the respective operators. We followed this latter approach and look only for solutions close to the standard model values.

The most recent, combined measurement of the cross section for top-antitop production is in good agreement with the most up-to-date theoretical prediction within the standard model and this result can be used to put constraints on the compositeness of the top quark. Current measurements of the cross sections set a stringent limit on the scale of compositeness. This limit is comparable to similar limits obtained for light quarks and those from electroweak precision measurements. It can also be used to constrain the parameter space of many composite Higgs models.

This work is presented in arXiv:1307.5750 [hep-ph].

The second project I was working on, together with some collaborators from SISSA (Trieste) and Fudan University (Shanghai), consists in using the exact renormalization group equation to compute the ordinary perturbative effective action in quantum field theory.

The exact renormalization group equation describes the functional renormalization group flow of the effective average action. The ordinary effective action is obtained by integrating the flow equation from an ultraviolet scale down to zero.

In this work we present several examples of such calculation at one-loop, both in renormalizable and in effective field theories. I was involved mainly in reproducing with this technique the four point scattering amplitude in scalar quantum field theories. I studied in particular the case of a real scalar field theory with quartic potential and the case of the pion chiral lagrangian. We considered also gauge theories, reproducing the vacuum polarization of QED and Yang Mills. We also compute the two point functions for scalars and gravitons in the effective field theory of scalar fields minimally coupled to gravity.

The functional renormalization group is a way of studying the flow of infinitely many couplings as functions of an externally imposed cutoff. The idea originates from Wilson's understanding of the renormalization group as the change in the action that is necessary to obtain the same partition function when one flows towards the infrared starting from an ultraviolet cutoff.
In particle physics one is usually more interested in the effective action than in the partition function, so one may anticipate that an equation describing the flow of the generator of one-particle irreducible Green functions may be of even greater use. For this purpose, the convenient functional to use is the effective average action. It is defined basically in the same way as the ordinary effective action, adding to the bare action a quadratic cutoff term. The effect of this term is to suppress the propagation of low momentum modes leaving the vertices unchanged.

This equation has been widely used in studies of the infrared properties of statistical and particle physics models, in particular of phase transitions and critical phenomena. It has also been used to study the ultraviolet behavior of gravity, in particular to establish the existence of a nontrivial fixed point which may be used to define a continuum limit. In this project we discussed some examples taken from particle physics where the exact renormalization group equation is used instead as a tool to compute the effective action at one-loop.

This work will be presented in a forthcoming preprint that will be submitted for publication by the beginning of 2014.

Research plan

In this period I started working together with some people at ICTP-SAIFR on direct and indirect bounds on Standard Model dimension six operators, focusing mainly on the so called 'dipole operators'.

These 'dipole operators' have direct effects on LHC observables because they give contributions to some physical observables that are going to be measured with an increasing precision in the next years. Preliminary LHC results about single top production cross section, W boson helicity fraction from top decay and top quark production in association to a weak vector boson are in agreement with the standard model predictions and these results can be used to put constraints on effective operators coefficients. I have performed a preliminary study about the effects of these dipole operators on these LHC observables. In particular, using FeynRules and Madgraph 5, I have computed the contribution of these effective operators at linear order in the effective couplings to single top production cross section, W boson helicity fraction from top decay and top quark production in association to a Z and W vector boson. From these results I have set some preliminary 95% confidence level bounds on single operator coefficients.

On the other hand, beside direct effects, dimension six operators can have indirect effects on electroweak precision measurements as well as on Higgs observables, occurring through operator mixing. These effect can be studied computing the renormalization group anomalous dimension mixing matrix. The standard way to perform this computation is by means of Feynman diagrams which in this case can be quite involved due to large number of them. An alternative approach we decided to follow consists in using heat kernel techniques.
As a preliminary result, I have computed using heat kernel techniques loops of third generation quarks which represent the renormalization group mixing matrix contributions to the pure bosonic operators coming for dimension six operators of the fermion/boson mixed form.

The plan for the next months is to extend the preliminary study of direct bounds on dipole dimension six operators including other relevant processes such as top-antitop-higgs production and performing a combined exclusion analysis in which more than one operator is considered at the same time. For what concerns the indirect bounds study, I want to extend the preliminary heat kernel computation considering also bosonic and mixed loops my means of using super heat kernel techniques, in order to obtain a full renormalization group mixing matrix.

I am also interesting in continuing the study of ultraviolet properties of quantum field theories in order to put asymptotic safety on a firmer ground.

The exact renormalization group equation is a powerful tool that is widely use to study , in principle, nonperturbatively the ultraviolet properties of any quantum field theory, regardless the fact that it is defined by a bare renormalizable lagrangian. In particular, this functional flow equation is usually used to study the existence of (ultraviolet) fixed points in theory space. Effective field theories are usually defined with a physical cutoff that sets the high energy limit for the validity of the theory. At scales of order of the cutoff some physical quantities starts to not behave properly, violating for example unitarity. Recently there have been some suggestions that nonperturbative effects may actually heal effective field theories of these problems. One possibility is that the renormalization group of the theory has a fixed point and the real world correspond to a trajectory that ends at the fixed point in the ultraviolet. This is known as asymptotic safety and its equivalent to a nonperturbativative notion of renormalizability. The good behavior of the coupling as a function of some unphysical renormalization group scale should reflect itself into a good behavior of physical amplitudes as a function of the external momenta. As emphasized by Weinberg, in discussing asymptotic safety it would be best to define the couplings directly in terms of observable quantities. Since it is much easier to define the running of couplings defined as coefficients of field monomials in the Lagrangian, so far most of the work has concentrated on the latter. One might expect that a fixed point for the Lagrangian coefficients would translate also in a fixed point for couplings defined in more physical terms.

The plan for the next year is to develop some work in this direction. A preliminary study about scalar field theories in dimension 3 and non-linear sigma models in dimension 4 are encouraging. The goal is to present a self consistent computation and possibly to extend those results also to gauge theories.

Preprints and publications

The work on top quark compositeness is presented in arXiv:1307.5750 [hep-ph] and has been submitted to publication to Physical Review D.

Conferences and workshops

I have been invited to the "Workshop de Física César Natividade" on November 26 in Guaratinguetá (SP) in which I gave a talk about the top quark compositeness study.

I will attend the 5th International Workshop High Energy Physics in the LHC era, Valparaiso (Chile) from 16 to 20 December 2013, in which I am going to present the work on top quark compositeness.

Visiting

I spent three weeks visiting ICTP Trieste in September 2013 under the agreement between the two ICTP institutions. During that period I took the opportunity to complete the top quark compositeness paper and to work on the functional renormalization group project.