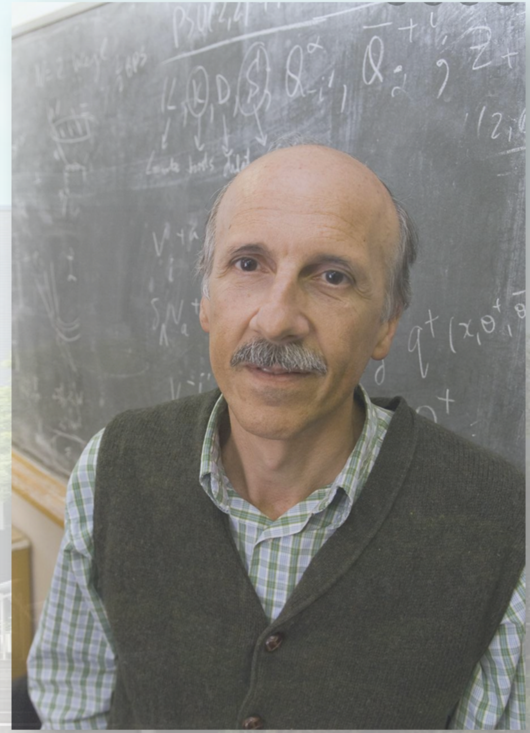
Strings and Large Extra Dimensions

Prof. Dieter Lüst
LMU (Arnold-Sommerfeld-Center) &
Max Planck Institute München



Planck 2022 at Ecole Polytechnique Ignatios Fest,
03. June 2022

Outline

Some contributions of Ignatios to theoretical physics

Experimental signatures of string theory

Gravitino mass and the swampland

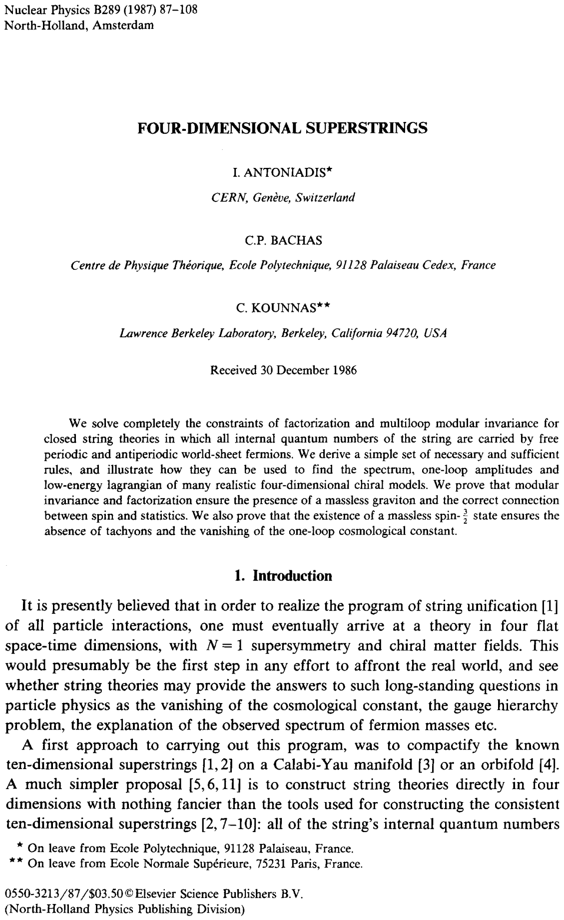
Massive U(1) Vector Bosons

Some contributions of Ignatios to theoretical physics

Ignatios Antoniadis made several profound contributions to theoretical physics.

His work is characterised by relating fundamental physics to experimental observations.

1986: Construction of four-dimensional fermionic strings



Nuclear Physics B289 (1987) 87–108
North-Holland, Amsterdam

FOUR-DIMENSIONAL SUPERSTRINGS

I. ANTONIADIS*

CERN, Genève, Switzerland

C.P. BACHAS

Centre de Physique Théorique, Ecole Polytechnique, 91128 Palaiseau Cedex, France

C. KOUNNAS**

Lawrence Berkeley Laboratory, Berkeley, California 94720, USA

Received 30 December 1986

We solve completely the constraints of factorization and multiloop modular invariance for closed string theories in which all internal quantum numbers of the string are carried by free periodic and antiperiodic world-sheet fermions. We derive a simple set of necessary and sufficient rules, and illustrate how they can be used to find the spectrum, one-loop amplitudes and low-energy lagrangian of many realistic four-dimensional chiral models. We prove that modular invariance and factorization ensure the presence of a massless graviton and the correct connection between spin and statistics. We also prove that the existence of a massless spin-$\frac{3}{2}$ state ensures the absence of tachyons and the vanishing of the one-loop cosmological constant.

1. Introduction

It is presently believed that in order to realize the program of string unification [1] of all particle interactions, one must eventually arrive at a theory in four flat space-time dimensions, with $N=1$ supersymmetry and chiral matter fields. This would presumably be the first step in any effort to affront the real world, and see whether string theories may provide the answers to such long-standing questions in particle physics as the vanishing of the cosmological constant, the gauge hierarchy problem, the explanation of the observed spectrum of fermion masses etc.

A first approach to carrying out this program, was to compactify the known ten-dimensional superstrings [1, 2] on a Calabi-Yau manifold [3] or an orbifold [4]. A much simpler proposal [5, 6, 11] is to construct string theories directly in four dimensions with nothing fancier than the tools used for constructing the consistent ten-dimensional superstrings [2, 7–10]: all of the string's internal quantum numbers

---

* On leave from Ecole Polytechnique, 91128 Palaiseau, France.
** On leave from Ecole Normale Supérieure, 75231 Paris, France.

0550-3213/87/$03.50
(North-Holland Physics Publishing Division)

1989: An expanding universe in string theory:

Nuclear Physics B328 (1989) 117–139
North-Holland, Amsterdam

AN EXPANDING UNIVERSE IN STRING THEORY

I. ANTONIADIS and C. BACHAS

Centre de Physique Theorique, Ecole Polytechnique, 91128 Palaiseau, France

John ELLIS

CERN, Geneva, Switzerland

D.V. NANOPOULOS

Physics Department, Texas A&M University, College Station, Texas, USA

Received 14 April 1989

We present solutions of the bosonic, heterotic and type II string theories, whose space-time manifold is a linearly expanding homogeneous and isotropic universe. These solutions are obtained by giving a background charge to the time coordinate on the world-sheet. We find the spectrum, demonstrate positivity of the Hilbert space up to the second excited level, and construct modular-invariant partition functions. The central charge of transverse excitations is a free parameter that controls the asymptotic density of states; the critical dimension and gauge group can in particular be made arbitrarily large. We show how to construct dual, factorizable, energy-conserving amplitudes in this background, discuss their interpretation and comment on the initial singularity and flatness problems in the light of our results.

1. Introduction

Nowadays the radius of the universe is much larger than the Planck length, or any other fundamental physical scale, and its curvature is correspondingly very small. Therefore it is normally thought to be a good approximation in particle physics to neglect the expansion of the universe, and treat the four large space-time dimensions as infinite and flat. This is why strings have been mostly studied up to now in four- or higher-dimensional Minkowski space-time. The role of a non-trivial gravitational background has received very little attention, even in attempts to discuss the physics of the early universe. This is somewhat paradoxical, because strings have been mainly advocated as consistent quantum theories of gravity (for a review see ref. [1]). It is therefore precisely in non-trivial gravitational settings that one should expect our field theory intuition to fail completely, and string theory to teach us something new and interesting. The purpose of this paper is to study string

0550-3213/89/$03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

1990: A possible new dimension at a few TeV

Volume 246, number 3,4 PHYSICS LETTERS B 30 August 1990

A possible new dimension at a few TeV

I. Antoniadis
Centre de Physique Théorique, Ecole Polytechnique, F-91128 Palaiseau, France
and CERN, CH-1211 Geneva 23, Switzerland

Received 13 June 1990

We examine the possibility of the existence of a large internal dimension at relatively low energies of the order of a few TeV. Such a dimension is a general prediction of perturbative string theories, which relate its size to the supersymmetry breaking scale. We point out that, contrary to our naive expectations, this scenario is consistent with perturbative unification up to the Planck scale, in a particular class of "four"-dimensional string models. Furthermore, it has spectacular phenomenological consequences, whose main effects are discussed.

A main problem in string phenomenology is the mechanism which breaks space–time supersymmetry. The latter is expected to occur at low energies, of the order of the electroweak scale, to protect the gauge hierarchy. Besides, this mechanism is crucial in string model building in order to destroy the flat directions and make definite predictions for the various masses and couplings. Surprisingly, despite the (infinitely) large degeneracy of four-dimensional string vacua, the spontaneous breaking of supersymmetry at a scale m_s much smaller than the Planck mass M_{Pl} turns out to be a very hard problem, at least in perturbation theory [1,2].

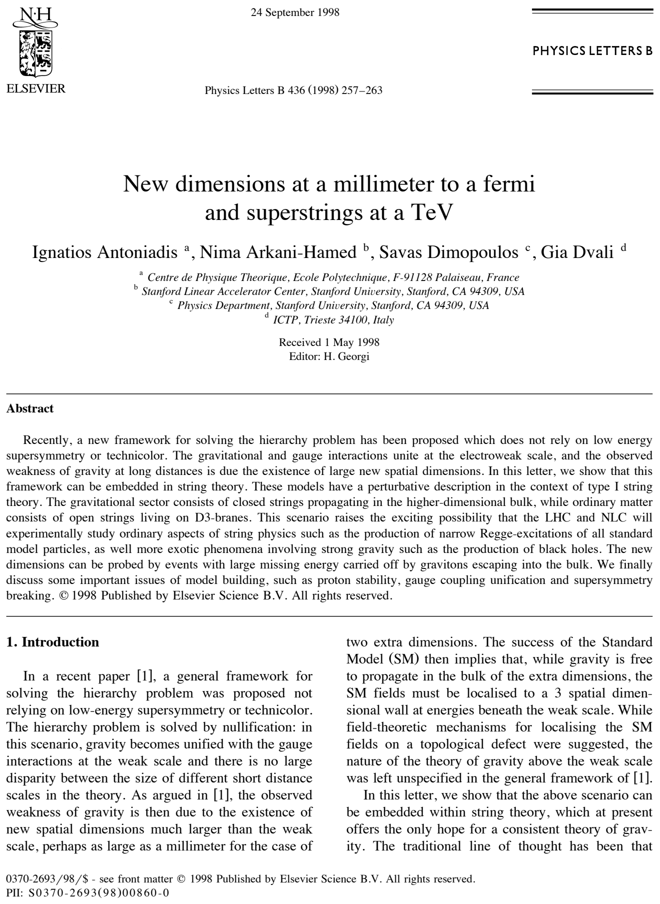
The first obvious question to ask is whether this scale could correspond to an arbitrary, at the tree level, continuous parameter, as is the case in ordinary supergravity. In string theories though, the only continuous parameters are vacuum expectation values (VEVs) of scalar fields along flat directions of their potential. These, in principle, cannot break supersymmetry spontaneously, since it is well known that the super-Higgs effect is not a usual Higgs phenomenon but needs nonvanishing VEVs for the auxiliary fields of the supermultiplets. In fact, space–time supersymmetry requires the world-sheet action to have $N=2$ superconformal invariance. The continuous breaking is then reduced to the problem of connecting smoothly $N=2$ to $N=1$ 2D superconformal theories, which is shown to be impossible [2].

This result does not rule out the possibility of making m_s small by tuning some discrete parameter. Furthermore, following some supergravity examples, one could have a large gravitino mass but still a small observable breaking scale, characterized for instance by the gaugino or scalar masses. This would amount again to a "discrete fine-tuning", because in string theories all these masses are proportional: in the limit of massless gauginos the gravitino becomes massless, as well. The existence of such a discrete parameter seems unlikely, although there is no general proof.

The final possibility is that m_s is related to some other continuous parameter of the theory, such as an internal compactification radius. In this case, the broken theory is continuously connected to the supersymmetric one, only in the decompactification limit which is infinitely far away. Some explicit examples of this kind have been worked out in the literature [3,4]. There are several reasons to believe that this is the only way to obtain a small supersymmetry breaking scale in string perturbation theory. In fact, the problem can be studied in a general way in a large class of four-dimensional models, the so-called "gaussian" models, which are constructed using free bosons or free fermions on the world-sheet. It has been shown [1] that the scale m_s can be small only if it is linked to the size of some internal dimension, which

0370-2693/90/$ 03.50 © 1990 – Elsevier Science Publishers B.V. (North-Holland)

1998: New dimensions at a millimeter and superstrings at a TeV



ELSEVIER

24 September 1998

Physics Letters B 436 (1998) 257–263

PHYSICS LETTERS B

New dimensions at a millimeter to a fermi and superstrings at a TeV

Ignatios Antoniadis [a], Nima Arkani-Hamed [b], Savas Dimopoulos [c], Gia Dvali [d]

[a] *Centre de Physique Theorique, Ecole Polytechnique, F-91128 Palaiseau, France*
[b] *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA*
[c] *Physics Department, Stanford University, Stanford, CA 94309, USA*
[d] *ICTP, Trieste 34100, Italy*

Received 1 May 1998
Editor: H. Georgi

Abstract

Recently, a new framework for solving the hierarchy problem has been proposed which does not rely on low energy supersymmetry or technicolor. The gravitational and gauge interactions unite at the electroweak scale, and the observed weakness of gravity at long distances is due the existence of large new spatial dimensions. In this letter, we show that this framework can be embedded in string theory. These models have a perturbative description in the context of type I string theory. The gravitational sector consists of closed strings propagating in the higher-dimensional bulk, while ordinary matter consists of open strings living on D3-branes. This scenario raises the exciting possibility that the LHC and NLC will experimentally study ordinary aspects of string physics such as the production of narrow Regge-excitations of all standard model particles, as well more exotic phenomena involving strong gravity such as the production of black holes. The new dimensions can be probed by events with large missing energy carried off by gravitons escaping into the bulk. We finally discuss some important issues of model building, such as proton stability, gauge coupling unification and supersymmetry breaking. © 1998 Published by Elsevier Science B.V. All rights reserved.

---

1. Introduction

In a recent paper [1], a general framework for solving the hierarchy problem was proposed not relying on low-energy supersymmetry or technicolor. The hierarchy problem is solved by nullification: in this scenario, gravity becomes unified with the gauge interactions at the weak scale and there is no large disparity between the size of different short distance scales in the theory. As argued in [1], the observed weakness of gravity is then due to the existence of new spatial dimensions much larger than the weak scale, perhaps as large as a millimeter for the case of two extra dimensions. The success of the Standard Model (SM) then implies that, while gravity is free to propagate in the bulk of the extra dimensions, the SM fields must be localised to a 3 spatial dimensional wall at energies beneath the weak scale. While field-theoretic mechanisms for localising the SM fields on a topological defect were suggested, the nature of the theory of gravity above the weak scale was left unspecified in the general framework of [1].

In this letter, we show that the above scenario can be embedded within string theory, which at present offers the only hope for a consistent theory of gravity. The traditional line of thought has been that

PII: S0370-2693(98)00860-0

Experimental signatures of string theory

Four-dimensional Planck mass in terms of 3 string parameters:

$$M_{\mathrm{Planck}}^{2} \simeq g_{\mathrm{string}}^{-2} M_{\mathrm{string}}^{8} \mathcal{V}_{6}$$

How to get experimental access to string scale and size of internal space?

(i) Measurement of heavy string (Regge) excitations

This is possible if the fundamental string scale is low,

$$M_{\rm string}/M_{\rm Planck} << 1$$

$$\Rightarrow \quad g_{\rm string} << 1 \quad \text{or} \quad \mathcal{V}_6 >> L^6_{\rm string}$$

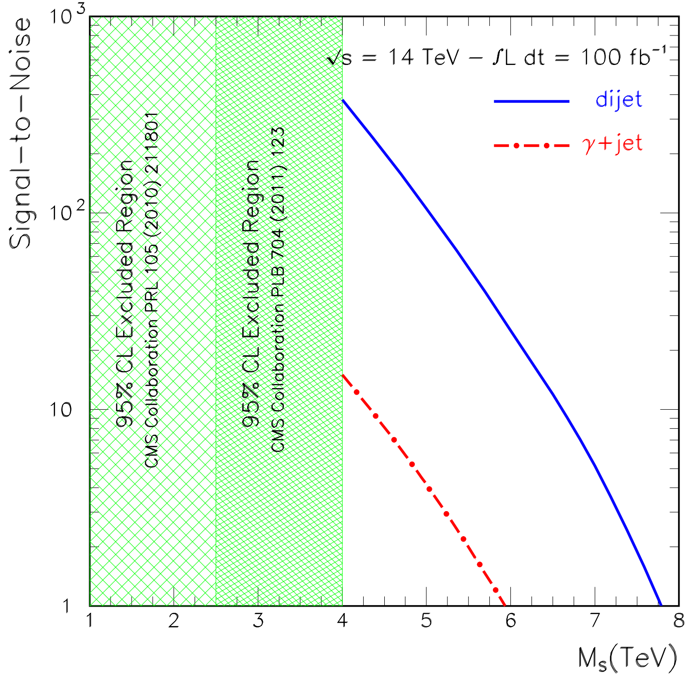
Small instants and little string theories

[E. Witten (2005);
K. Benakli, Y. Oz (1999);
A. Antoniadis, S. Dimopoulos,
A. Giveon (2001)]

Large volume string compactifications

[I. Antoniadis, N. Arkani Hamed,
S. Dimopoulos, G. Dvali (1998);
V. Balasubramanian, P. Berglund,
J. Conlon, F. Quevedo (2005)]

(String Hunters’ Companion: Concrete calculations of cross sections: Model independent results, i.e. true for a large class of string compactifiactions
S. Stieberger, T. Taylor, D. L.: 2008/2009)



Best bound today: $LHC: \qquad M_{\text{string}} \geq \mathcal{O}(7TeV)$

(ii) Large extra dimensions:

Kaluza-Klein states from compact internal geometry

→ Deviation from Newtonian gravity

$$R_{\rm compact.} \leq \mathcal{O}(\mu\,{\rm meter})$$

(iii) Low energy supersymmetry & (iv) „Exotic“ light string states:

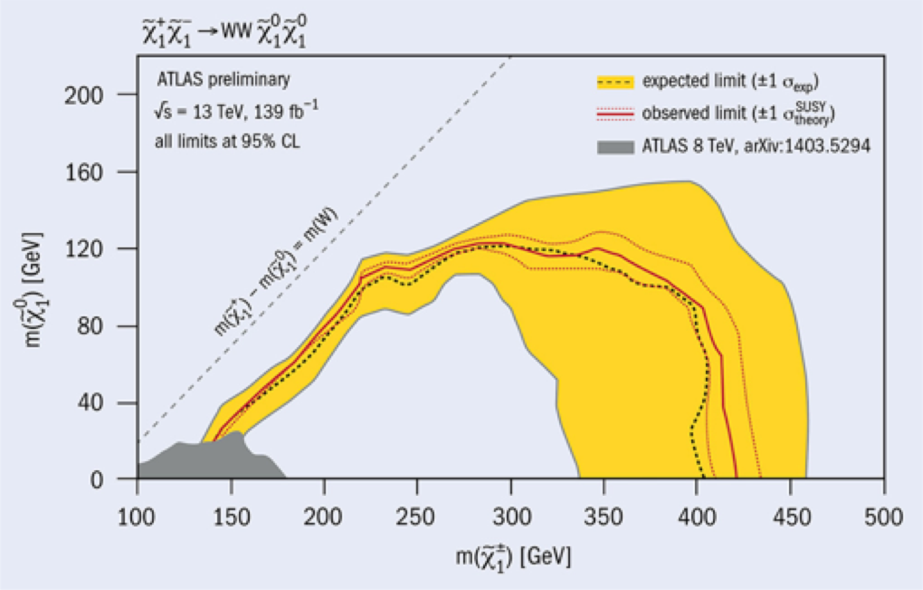
Low energy supersymmetry: See next section

„Exotic“ light string states: e.g. Light Z′ gauge bosons

Gravitino mass and the swampland

Apparently low energy supersymmetry is not favoured by experiments:

$$M(\text{Susy partner}) > \mathcal{O}(TeV)$$



Is there any fundamental reason against low energy supersymmetry?

The scale of susy breaking is set by the gravitino:

$$\boxed{M_{SUSY}^2 \simeq m_{3/2}\, M_P}$$

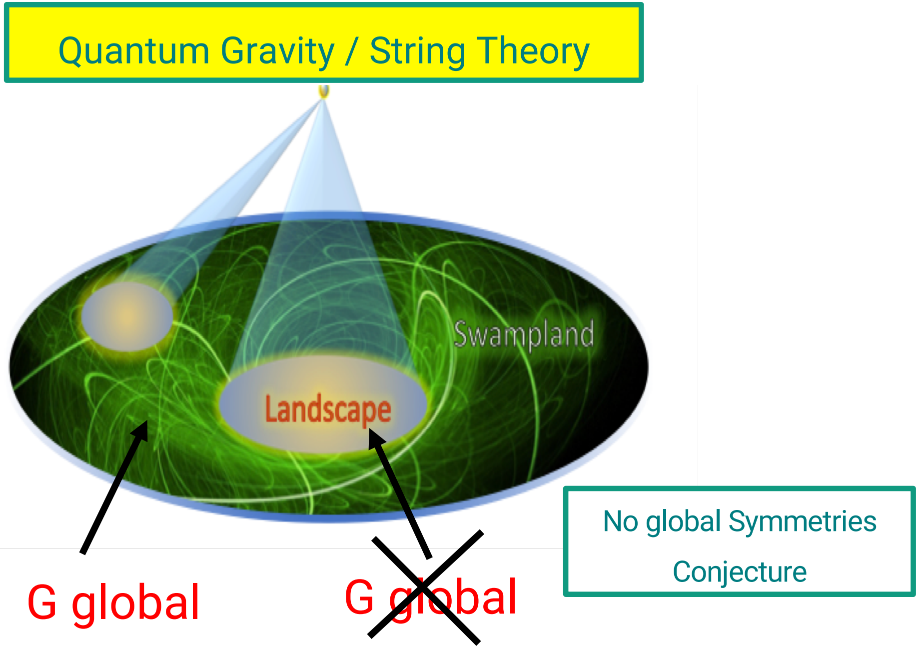
Exp: $m_{3/2} \geq \mathcal{O}(10^{-3}\mathrm{eV})$

Is there any fundamental reason against a light gravitino?

Can we get information about the scale of Susy breaking, i.e. about the mass of the gravitino from basic properties of quantum gravity ?

Swampland Idea:

Which IR consistent quantum field theories cannot be embedded into a UV complete quantum gravity theory?
C. Vafa, 2005



Quantum Gravity / String Theory

G global

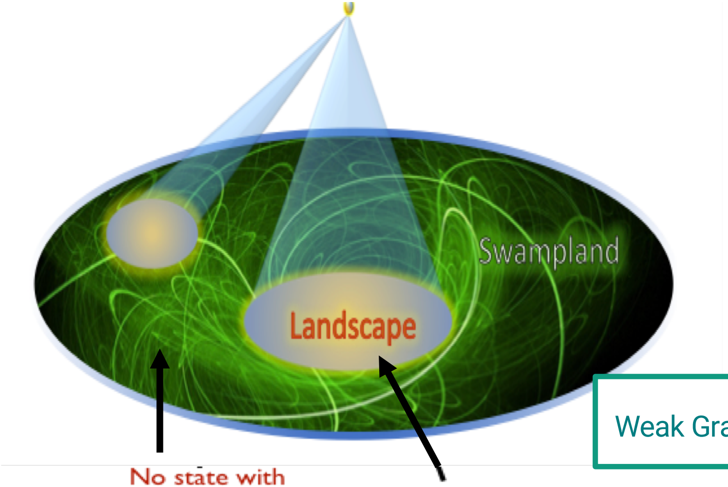
~~G global~~

No global Symmetries Conjecture

Swampland Idea:

Which IR consistent quantum field theories cannot be embedded into a UV complete quantum gravity theory?
C. Vafa, 2005

Quantum Gravity / String Theory



No state with
$q \geq m$

Exist state with
$q \geq m$

Weak Gravity Conjecture

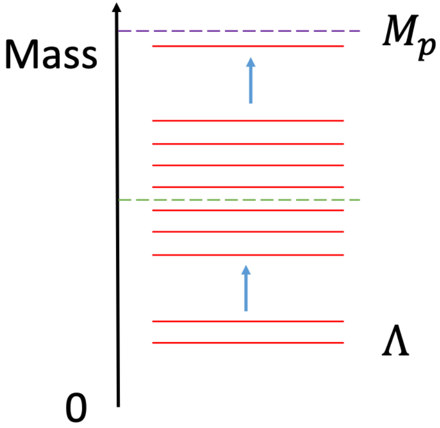
Swampland distance conjecture:

At large distance directions in the parameter space of string vacua there must be an infinite tower of states with mass scale m.

SDC: $\boxed{m = M_P e^{-\Delta}}$ [H. Ooguri, C.Vafa (2006)]

EFT breaks down at $\Lambda_{QG} \sim m^{\alpha}$ (species scale). [G. Dvali (2007)]

$\Lambda_{QG} << M_P$ when $\Delta \to \infty$



Emergent String Conjecture:

S. Lee, W. Lerche, T. Weigand (2019)

At large distances there can be only two kind of towers:

(i) KK particles and winding strings:

$$m_{KK} \simeq \frac{1}{R} \quad \text{or} \quad m_{wind} \simeq R$$

Related distance in the internal moduli space:

$$\Delta_R \simeq |\log R| \to \infty \quad \text{for} \quad R \to \infty, 0$$

(ii) Massive string excitations $m_s \simeq g_s$

$$\Delta_s \simeq |\log g_s| \to \infty \quad \text{for} \quad g_s \to 0, \infty$$

Gravitino Mass Conjecture:

N. Cribiori, M. Scalisi, D.L. ; A. Castellano, A. Font. A. Harraez, L. Ibanez (2021)

In the limit of small gravitino mass there exist an infinite tower of states with mass scale m, which behaves as:

GMC:

$$\boxed{m \sim (m_{3/2})^n \quad \text{with} \quad n > 0}$$

Why the GMC can be true:

(i) The gravitino mass is related to extra dimensions.

The GMC follows from the distance conjecture.

See also I. Antoniadis, C. Bachas, D. Lewellen, T. Tomaras (1988)

(ii) The gravitino mass is related to a U(1) gauge coupling

The GMC follows from the (magnetic) weak gravity conjecture.

Combine the GMC with inflation

The mass scale of inflation in the EFT is determined by the Hubble parameter H. For consistency one needs

$$H < \Lambda_{QG}$$

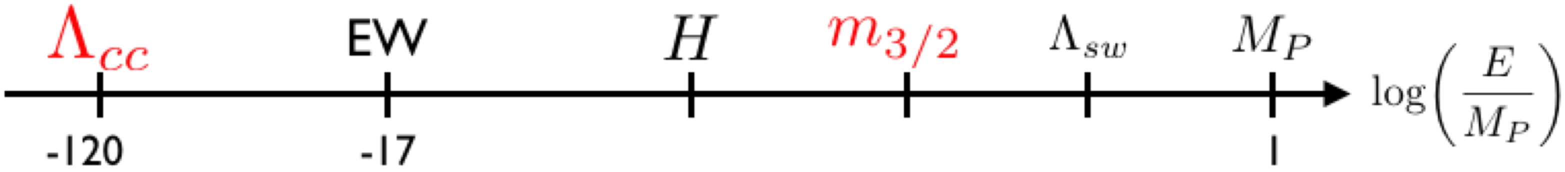
This translate into the following lower bound on the gravitino mass

$$m_{3/2} > M_P^{\frac{n-3}{n}} H^{\frac{3}{n}}$$

E.g. for $n = 3$ $m_{3/2} > H$ [see also R. Kallosh, A. Linde (2004)]

Combine the GMC with inflation

Susy breaking scale is of order or higher than the Hubble scale H of inflation!



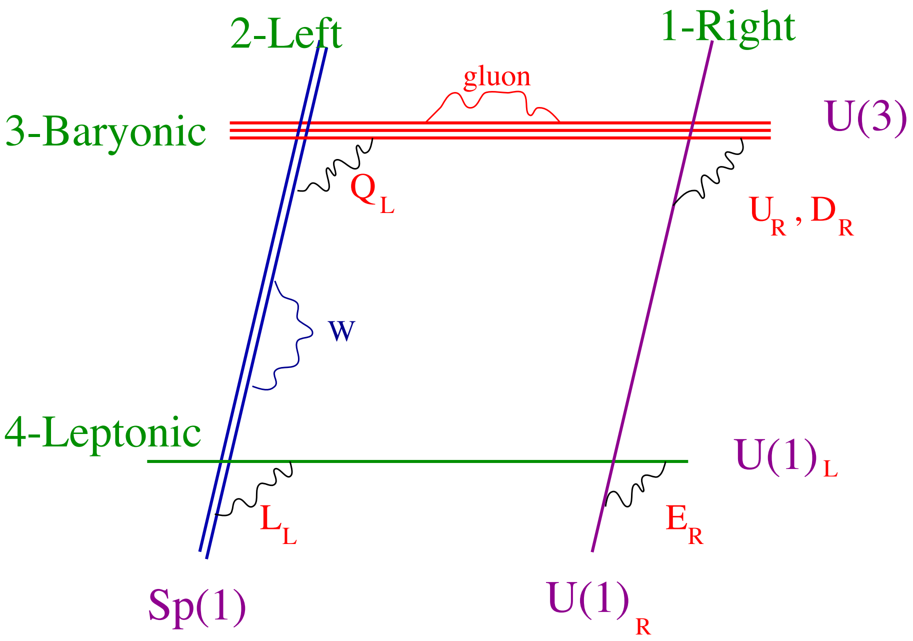
Massive U(1) Vector Bosons

Joint work with Ignatios: **in total 16 common papers**

Many of them are about massive Z’ bosons and their possible experimental signatures.

Z’ arise naturally in intersecting D-brane compactifications with a low string scale:

See e.g. R. Blumenhagen, B. Körs, D.L., S. Stieberger (2006)



The Z’ gauge boson arises as a linear combination of four U(1)’s.

I. Antoniadis, E. Kiritsis, J. Rizos (2002)

Z’ can get a mass in two ways:

$$\text{anomalous } U(1)_a : \quad M_{Z'} = g_a M_{\text{string}}$$

$$\text{non} - \text{anomalous } U(1)_a : \quad M_{Z'} = g_a M^3_{\text{string}} V_2$$

$$g_a \propto \frac{g_s}{\sqrt{\mathcal{V}_{\|}}}$$

Now consider several cases…

(i) Z' as harbinger of low string scale (leptophobic Z')

Possible signals at hadron colliders.

→ Z' couples primarily to quarks

MPP–2011–86
LMU-ASC 32/11
CERN-PH-TH/2011-180

arXiv:1107.4309v3 [hep-ph] 24 Mar 2012

Z'-gauge Bosons as Harbingers of Low Mass Strings

Luis A. Anchordoqui,[1] **Ignatios Antoniadis**,[2,*] **Haim Goldberg**,[3]
Xing Huang,[4] **Dieter Lüst**,[5,6] and **Tomasz R. Taylor**[3]

[1]*Department of Physics,*
University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

[2]*Department of Physics,*
CERN Theory Division, CH-1211 Geneva 23, Switzerland

[3]*Department of Physics,*
Northeastern University, Boston, MA 02115, USA

[4]*School of Physics and Astronomy,*
Seoul National University, Seoul 141-747, Korea

[5]*Max–Planck–Institut für Physik,*
Werner–Heisenberg–Institut, 80805 München, Germany

[6]*Arnold Sommerfeld Center for Theoretical Physics*
Ludwig-Maximilians-Universität München, 80333 München, Germany

Abstract

Massive Z'-gauge bosons act as excellent harbingers for string compactifications with a low string scale. In D-brane models they are associated to $U(1)$ gauge symmetries that are either anomalous in four dimensions or exhibit a hidden higher dimensional anomaly. We discuss the possible signals of massive Z'-gauge bosons at hadron collider machines (Tevatron, LHC) in a minimal D-brane model consisting out of four stacks of D-branes. In this construction, there are two massive gauge bosons, which can be naturally associated with baryon number B and $B - L$ (L being lepton number). Here baryon number is always anomalous in four dimensions, whereas the presence of a four-dimensional $B - L$ anomaly depends on the $U(1)$-charges of the right handed neutrinos. In case $B - L$ is anomaly free, a mass hierarchy between the two associated Z'-gauge bosons can be explained. In our phenomenological discussion about the possible discovery of massive Z'-gauge bosons, we take as a benchmark scenario the dijet plus W signal, recently observed by the CDF Collaboration at Tevatron. It reveals an excess in the dijet mass range 150 GeV/c^2, 4.1σ beyond SM expectations. We show that in the context of low-mass string theory this excess can be associated with the production and decay of a leptophobic Z', a singlet partner of $SU(3)$ gluons coupled primarily to baryon number. Even if the CDF signal disappears, as indicated by the more recent D0 results, our analysis can still serve as the basis for future experimental search for massive Z'-gauge bosons in low string scale models. We provide the relevant cross sections for the production of Z'-gauge bosons in the TeV region, leading to predictions that are within reach of the present or the next LHC run.

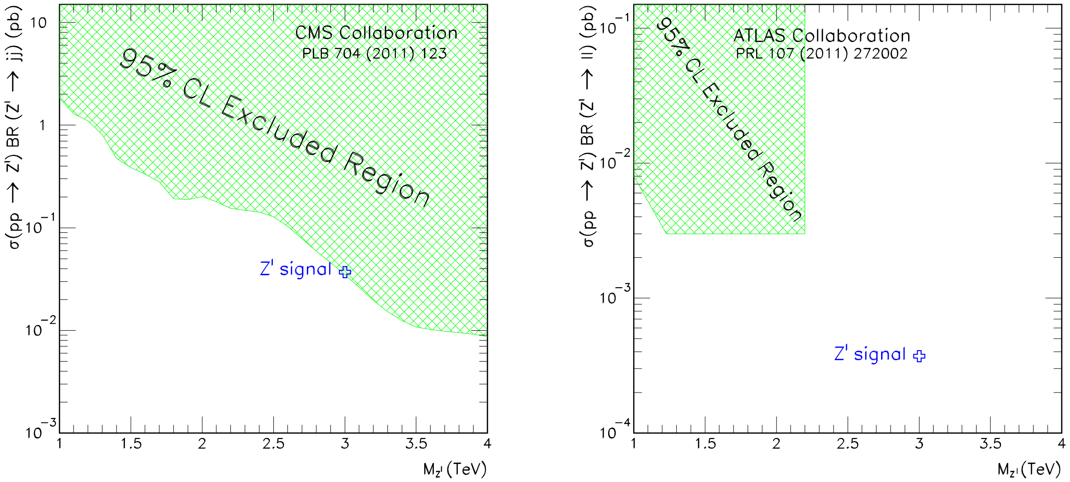
---

[*] On leave of absence from CPHT Ecole Polytechnique, F-91128, Palaiseau Cedex.

(i) Z' as harbinger of low string scale (leptophobic Z')

$$\hat{\sigma}(q\bar{q} \to Z') = K\frac{2\pi}{3}\,\frac{G_F\,M_Z^2}{\sqrt{2}}\,\left[v_q^2(\phi, g_1') + a_q^2(\phi, g_1')\right]\,\delta\left(\hat{s} - M_{Z'}^2\right)$$

Exclusion plots by CMS and ATLAS from 2011:



(ii) Z' as dark matter candidate

MPP-2020-121
LMU-ASC 34/20

Anomalous $U(1)$ Gauge Bosons as Light Dark Matter in String Theory

Luis A. Anchordoqui,[1,2,3] Ignatios Antoniadis,[4,5] Karim Benakli,[4] and Dieter Lüst[6,7]

[1]*Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA*
[2]*Department of Physics, Graduate Center, City University of New York, NY 10016, USA*
[3]*Department of Astrophysics, American Museum of Natural History, NY 10024, USA*
[4]*Laboratoire de Physique Théorique et Hautes Énergies - LPTHE Sorbonne Université, CNRS, 4 Place Jussieu, 75005 Paris, France*
[5]*Albert Einstein Center, Institute for Theoretical Physics University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[6]*Max–Planck–Institut für Physik, Werner–Heisenberg–Institut, 80805 München, Germany*
[7]*Arnold Sommerfeld Center for Theoretical Physics Ludwig-Maximilians-Universität München, 80333 München, Germany*

Present experiments are sensitive to very weakly coupled extra gauge symmetries which motivates further investigation of their appearance in string theory compactifications and subsequent properties. We consider extensions of the standard model based on open strings ending on D-branes, with gauge bosons due to strings attached to stacks of D-branes and chiral matter due to strings stretching between intersecting D-branes. Assuming that the fundamental string mass scale saturates the current LHC limit and that the theory is weakly coupled, we show that (anomalous) $U(1)$ gauge bosons which propagate into the bulk are compelling light dark matter candidates. We comment on the possible relevance of the $U(1)$ gauge bosons, which are universal in intersecting D-brane models, to the observed 3σ excess in XENON1T.

INTRODUCTION

The primary objective of the High Energy Physics (HEP) program is to find and understand what physics may lie beyond the Standard $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ Model (SM), as well as its connections to gravity and to the hidden sector of particle dark matter (DM). This objective is pursued in several distinct ways. In this Letter, we explore one possible pathway to join the vertices of the HEP triangle using string compactifications with large extra dimensions [1], where sets of D-branes lead to chiral gauge sectors close to the SM [2, 3].

D-branes provide a nice and simple realization of non-abelian gauge symmetry in string theory. A stack of N identical parallel D-branes eventually generates a $U(N)$ theory with the associated $U(N)$ gauge group where the corresponding gauge bosons emerge as excitations of open strings ending on the D-branes. Chiral matter is either due to strings stretching between intersecting D-branes, or to appropriate projections on strings in the same stack. Gravitational interactions are described by closed strings that can propagate in all dimensions; these comprise parallel dimensions extended along the D-branes and transverse ones.

String compactifications could leave characteristic footprints at particle colliders:

- the emergence of Regge recurrences at parton collision energies $\sqrt{s} \sim$ string mass scale $\equiv M_s = 1/\sqrt{\alpha'}$ [4–6];
- the presence of one or more additional $U(1)$ gauge symmetries, beyond the $U(1)_Y$ of the SM [7–9].

Herein we argue that the (anomalous) $U(1)$ gauge bosons that do not partake in the hypercharge combination could become compelling dark matter candidates. Indeed, as noted elsewhere [10] these gauge fields could live in the bulk and the four-dimensional $U(1)$ gauge coupling would become infinitesimally small in low string scale models, $g \sim M_s/M_{\rm Pl}$, where $M_{\rm Pl}$ is the Planck mass (for previous investigations in different regions of parameters and different string scenarios, see for example [11–13]). Note that for typical energies E of the order of the electron mass, the value of g is still bigger that the gravitational coupling $\sim E/M_{\rm Pl}$, and the strength of the new force would be about 10^7 times stronger than gravity, where we have taken $M_s \sim 8$ TeV, saturating the LHC bound [14].

To develop some sense for the orders of magnitude involved, we now make contact with the experiment. The XENON1T Collaboration has recently reported a surplus of events in $1 \lesssim$ electronic recoils/keV $\lesssim 7$, peaked around 2.8 keV [15]. The total number of events recorded within this energy window is 285, whereas the expected background is 232 ± 15. Taken at face value this corresponds to a significance of roughly 3σ, but unknown backgrounds from tritium decay cannot be reliably ruled out [15]. Although the excess is not statistical significant, it is tempting to imagine that it corresponds to a real signal of new physics. A plethora of models have already been proposed to explain the excess, in which the DM particle could be either the main component of the abundance in the solar neighborhood, $n_{\rm DM} \sim 10^5\,(m_{\rm DM}/2.8~{\rm keV})^{-1}~{\rm cm}^{-3}$, or else a sub-component of the DM population. Absorption of a ~ 2.8 keV mass dark vector boson that saturates the local DM mass density provides a good fit to the excess for a $U(1)_X$ gauge coupling to electrons of $g_{X,{\rm eff}} \sim 2\times10^{-16} - 8\times10^{-16}$ [15–20]. For such small masses and couplings, the cosmological production should be non-thermal [17], avoiding constraints from structure formation [21, 22]. Leaving aside attempts to fit the XENON1T excess, we might consider a wider range of dark photon masses and couplings. For light and very weakly coupled dark photons, the cooling of red giants and horizontal branch stars give stronger or similar bounds on $g_{X,{\rm eff}}$ than direct detec-

(iii) Leptophilic Z’ and anomalous magnetic moment of the muon.

MPP–2021–60
LMU-ASC 09/21

Muon $g-2$ discrepancy within D-brane string compactifications

Luis A. Anchordoqui,[1,2,3] **Ignatios Antoniadis**,[4,5]
Xing Huang,[6,7] **Dieter Lüst**,[8,9] and **Tomasz R. Taylor**[10]

[1]*Department of Physics and Astronomy,*
Lehman College, City University of New York, NY 10468, USA

[2]*Department of Physics,*
Graduate Center, City University of New York, NY 10016, USA

[3]*Department of Astrophysics,*
American Museum of Natural History, NY 10024, USA

[4]*Laboratoire de Physique Théorique et Hautes Énergies - LPTHE*
Sorbonne Université, CNRS, 4 Place Jussieu, 75005 Paris, France

[5]*Institute for Theoretical Physics,*
KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

[6]*Institute of Modern Physics,*
Northwest University, Xi’an 710069, China

[7]*Shaanxi Key Laboratory for Theoretical Physics Frontiers,*
Xi’an 710069, China

[8]*Max–Planck–Institut für Physik,*
Werner–Heisenberg–Institut, 80805 München, Germany

[9]*Arnold Sommerfeld Center for Theoretical Physics*
Ludwig-Maximilians-Universität München, 80333 München, Germany

[10]*Department of Physics,*
Northeastern University, Boston, MA 02115, USA

arXiv:2104.06854v3 [hep-ph] 15 Jun 2021

Abstract

Very recently, the Muon $g-2$ experiment at Fermilab has confirmed the E821 Brookhaven result, which hinted at a deviation of the muon anomalous magnetic moment from the Standard Model (SM) expectation. The combined results from Brookhaven and Fermilab show a difference with the SM prediction $\delta a_\mu = (251 \pm 59) \times 10^{-11}$ at a significance of 4.2σ, strongly indicating the presence of new physics. Motivated by this new result we reexamine the contributions to δa_μ from both: *(i)* the ubiquitous $U(1)$ gauge bosons of D-brane string theory constructions and *(ii)* the Regge excitations of the string. We show that, for a string scale $\mathcal{O}(\text{PeV})$, the contribution from anomalous $U(1)$ gauge bosons which couple to hadrons could help to reduce (though not fully eliminate) the discrepancy reported by the Muon $g-2$ Collaboration. Consistency with null results from LHC searches of new heavy vector bosons imparts the dominant constraint. We demonstrate that the contribution from Regge excitations is strongly suppressed as it was previously conjectured. We also comment on contributions from Kaluza-Klein (KK) modes, which could help resolve the δa_μ discrepancy. In particular, we argue that for 4-stack intersecting D-brane models, the KK excitations of the $U(1)$ boson living on the lepton brane would not couple to hadrons and therefore can evade the LHC bounds while fully bridging the δa_μ gap observed at Brookhaven and Fermilab.

(iii) Leptophilic Z’ and anomalous magnetic moment of the muon.

MPP-2021-68
LMU-ASC 12/21

arXiv:2105.02630v2 [hep-ph] 5 Oct 2021

Leptophilic $U(1)$ Massive Vector Bosons from Large Extra Dimensions

Luis A. Anchordoqui,[1,2,3] Ignatios Antoniadis,[4,5] Xing Huang,[6,7,8] Dieter Lüst,[9,10] and Tomasz R. Taylor[11]

[1]*Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA*
[2]*Department of Physics, Graduate Center, City University of New York, NY 10016, USA*
[3]*Department of Astrophysics, American Museum of Natural History, NY 10024, USA*
[4]*Laboratoire de Physique Théorique et Hautes Énergies - LPTHE Sorbonne Université, CNRS, 4 Place Jussieu, 75005 Paris, France*
[5]*Institute for Theoretical Physics, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*
[6]*Institute of Modern Physics, Northwest University, Xi’an 710069, China*
[7]*NSFC-SPTP Peng Huanwu Center for Fundamental Theory, Xi’an 710127, China*
[8]*Shaanxi Key Laboratory for Theoretical Physics Frontiers, Xi’an 710069, China*
[9]*Max–Planck–Institut für Physik, Werner–Heisenberg–Institut, 80805 München, Germany*
[10]*Arnold Sommerfeld Center for Theoretical Physics Ludwig-Maximilians-Universität München, 80333 München, Germany*
[11]*Department of Physics, Northeastern University, Boston, MA 02115, USA*

We demonstrate that the discrepancy between the anomalous magnetic moment measured at BNL and Fermilab and the Standard Model prediction could be explained within the context of low-scale gravity and large extra-dimensions. The dominant contribution to $(g-2)_\mu$ originates in Kaluza-Klein (KK) excitations (of the lepton gauge boson) which do not mix with quarks (to lowest order) and therefore can be quite light avoiding LHC constraints. We show that the KK contribution to $(g-2)_\mu$ is universal with the string scale entering as an effective cutoff. The KK tower provides a unequivocal distinctive signal which will be within reach of the future muon smasher.

Low scale gravity and large extra dimensions offer a genuine solution to the gauge hierarchy problem [1, 2]. Within these models one has to address the problem of baryon B and lepton L number violation by higher dimensional operators suppressed only by the low string scale M_s. Intersecting D-brane models offer a way out by gauging these symmetries [3–7]. Since the B and L gauge bosons are anomalous they gain masses through a generalization of the Green-Schwarz (GS) anomaly cancellation [8–11] giving rise to perturbative global symmetries broken only by non-perturbative effects that are suppressed exponentially by the string/gauge coupling. The resulting gauge bosons form in general linear combinations of the various abelian gauge factors orthogonal to the hypercharge combination, that couple to both quark and leptons. However, the Kaluza-Klein (KK) excitations do not mix (to lowest order) and thus those of L couple only to leptons. Such modes can be quite light because LHC constraints are weak but can provide a sizable contribution to the anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$.

TeV-scale D-brane string compactifications could then provide an innovative framework to explain the extant tension between the Standard Model (SM) prediction of a_μ and experiment. Very recently, the Muon $g-2$ Experiment at Fermilab reported a measurement reading $a_\mu^{\rm FNAL} = 116592040(54) \times 10^{-11}$ [12], which is larger than the SM prediction $a_\mu^{\rm SM} = 116591810(43) \times 10^{-11}$ in which contributions from QED, QCD, and electroweak interactions are taken into account with highest precision [13]. This leads to $a_\mu^{\rm FNAL} - a_\mu^{\rm SM} = (230 \pm 69) \times 10^{-11}$, which corresponds to a 3.2σ discrepancy. Because the Fermilab observation is compatible with the long-standing discrepancy from the E821 experiment at BNL [14], the overall deviation from the SM central value,

$$\Delta a_\mu^{\rm exp} \equiv a_\mu^{\rm FNAL+BNL} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}\,, \qquad (1)$$

strengthens the significance to 4.2σ [12].[1] Even though the discrepancy is not statistical significant yet, it is interesting to entertain the possibility that it corresponds to a real signal of new physics. In this Letter we calculate the massive vector boson contribution to $g-2$ from KK excitations of L and we show that it is *universal* and can accommodate the $\Delta a_\mu^{\rm exp}$ discrepancy of (1).

At the leading order in the $U(1)_L$ coupling constant g_L, the contribution of a massive vector boson to lepton’s $g-2$ originates from the vertex correction shown in Fig. 1. Note that KK momentum is not conserved in lepton gauge boson vertices since leptons are localized in brane intersections. Figure 1 shows the same diagram that yields the famous α/π in QED, but with the virtual photon replaced by a massive vector boson. The fastest way to compute it is to use the massive propagator in

---

[1] We note in passing that the SM prediction estimated by the latest lattice QCD calculations, $a_\mu^{\rm SM,lattice} = 11659195163(58) \times 10^{-11}$, has a larger uncertainty and brings the prediction closer to the experimental value, $a_\mu^{\rm FNAL+BNL} - a_\mu^{\rm SM,lattice} = 109(71) \times 10^{-11}$, yielding only a 1.6 σ effect [15].

(iii) Leptophilic Z’ and anomalous magnetic moment of the muon.

MPP-2021-175
LMU-ASC 42/21

Leptophilic $U(1)$ Massive Vector Bosons from Large Extra Dimensions: Reexamination of Constraints from LEP Data

Luis A. Anchordoqui,[1,2,3] Ignatios Antoniadis,[4] Xing Huang,[5,6,7]
Dieter Lüst,[8,9] François Rondeau,[4] and Tomasz R. Taylor[10]

[1]*Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA*
[2]*Department of Physics, Graduate Center, City University of New York, NY 10016, USA*
[3]*Department of Astrophysics, American Museum of Natural History, NY 10024, USA*
[4]*Laboratoire de Physique Théorique et Hautes Énergies - LPTHE Sorbonne Université, CNRS, 4 Place Jussieu, 75005 Paris, France*
[5]*Institute of Modern Physics, Northwest University, Xi’an 710069, China*
[6]*NSFC-SPTP Peng Huanwu Center for Fundamental Theory, Xi’an 710127, China*
[7]*Shaanxi Key Laboratory for Theoretical Physics Frontiers, Xi’an 710069, China*
[8]*Max–Planck–Institut für Physik, Werner–Heisenberg–Institut, 80805 München, Germany*
[9]*Arnold Sommerfeld Center for Theoretical Physics Ludwig-Maximilians-Universität München, 80333 München, Germany*
[10]*Department of Physics, Northeastern University, Boston, MA 02115, USA*

arXiv:2110.01247v2 [hep-ph] 10 Mar 2022

Very recently, we proposed an explanation of the discrepancy between the measured anomalous magnetic moment of the muon and the Standard Model (SM) prediction in which the dominant contribution to $(g-2)_\mu$ originates in Kaluza-Klein (KK) excitations (of the lepton gauge boson) which do not mix with quarks (to lowest order) and therefore can be quite light avoiding LHC constraints. In this addendum we reexamine the bounds on 4-fermion contact interactions from precise electroweak measurements and show that the constraints on KK masses and couplings are more severe than earlier thought. However, we demonstrate that our explanation remains plausible if a few KK modes are lighter than LEP energy, because if this were the case the contribution to the 4-fermion scattering from the internal propagator would be dominated by the energy and not by the mass. To accommodate the $(g-2)_\mu$ discrepancy we assume that the lepton number L does not partake in the hypercharge and propagates in one extra dimension (transverse to the SM branes): for a mass of the lowest KK excitation of 60 GeV (lower than the LEP energy), the string scale is roughly 10 TeV while the L gauge coupling is of order $\sim 10^{-1}$.

In [1] we argue that the exchange of Kaluza-Klein (KK) excitations of the lepton number (L) gauge boson could provide a dominant contribution to $(g-2)_\mu$ and explain the discrepancy between the Standard Model (SM) prediction of $a_\mu = (g-2)_\mu/2$ and experiment: $\Delta a_\mu^{\rm exp} \equiv a_\mu^{\rm FNAL+BNL} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}$ [2]. On the other hand, the zero mode of the lepton number gauge boson is anomalous and gains a mass $\mathcal{O}(M_s)$ through a four-dimensional generalisation of the Green-Schwarz anomaly cancellation mechanism. Its mass being at the string scale, its contribution to $(g-2)_\mu$ is negligible, and therefore only the contributions of the KK modes are relevant to explain the discrepancy. In this addendum we reexamine model constraints from LEP data.

At the leading order in the $U(1)_L$ coupling constant g_L, the contribution of massive vector bosons to $(g-2)_\mu$ comes from the muon vertex correction, and is given by

$$\Delta a_\mu = \frac{\alpha_L m_\mu^2}{\pi} \int_0^1 dx dy dz \delta(x+y+z-1) \frac{z(1-z)}{(1-z)^2 m_\mu^2 + z M^2}, \tag{1}$$

where M is the mass of the boson, m_μ the muon mass and $\alpha_L = g_L^2/(4\pi)$. One can then consider three different cases, depending whether $M \gg m_\mu$, $M \sim m_\mu$ or $M \ll m_\mu$.

Case 1 : $M \gg m_\mu$

When all KK states have masses much bigger than the muon mass, the sum of the integral (1) over all the KK states can be approximated by

$$\Delta a_\mu^{(1)} = \sum_n \frac{1}{3} \frac{\alpha_L(n)}{\pi} \frac{m_\mu^2}{M_n^2}, \tag{2}$$

where M_n is the mass of the nth KK excitation [1].

The bound from LEP data on the so-called compositeness scale associated to 4-fermion operators is given by [3]:

$$\left| \sum_n \frac{\alpha_L(n)}{s - M_n^2} \right| < B \sim (10\ {\rm TeV})^{-2}, \tag{3}$$

where s is the square of the center-of-mass energy[1]. For $M_n \gg \sqrt{s}$, (3) reduces to $\sum_n \alpha_L(n)/M_n^2 < B$. Thus, the

---

[1] For fine-tuned values of M_n close to $\sqrt{s}$, the vector boson propagator appearing in the left-hand side of (3) is regulated by replacing $\frac{1}{s-M_n^2}$

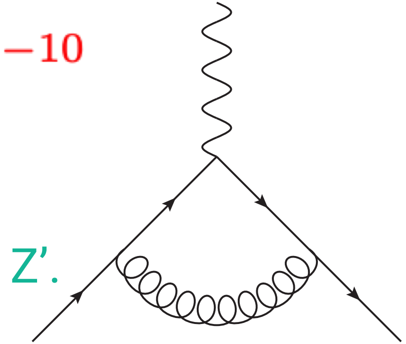
Deviation of the muon
anomalous magnetic moment
from the Standard Model:

$$\delta a_\mu = (251 \pm 59) \times 10^{-11}$$

Leptophilic Z' can at least in
part accommodate
for this deviation.

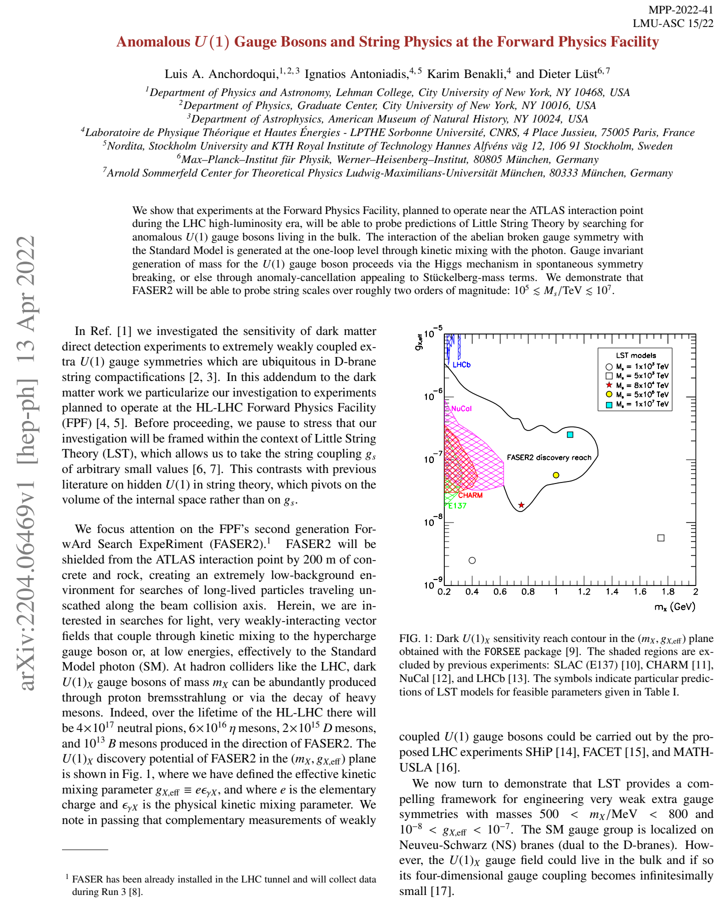
$$\Delta a_\mu = \frac{(g-2)_\mu}{2} = \frac{1}{3}\frac{\alpha_L}{\pi}\frac{m^2}{M_{Z'}^2}$$

$$\Longrightarrow \quad \Delta a_\mu \simeq 10^{-10}$$



Additional contributions are possible due to KK excitations of Z'.

(iv) Z’ gauge bosons and forward Physics Facilities



MPP-2022-41
LMU-ASC 15/22

Anomalous $U(1)$ Gauge Bosons and String Physics at the Forward Physics Facility

Luis A. Anchordoqui,[1,2,3] Ignatios Antoniadis,[4,5] Karim Benakli,[4] and Dieter Lüst[6,7]

[1]*Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA*
[2]*Department of Physics, Graduate Center, City University of New York, NY 10016, USA*
[3]*Department of Astrophysics, American Museum of Natural History, NY 10024, USA*
[4]*Laboratoire de Physique Théorique et Hautes Énergies - LPTHE Sorbonne Université, CNRS, 4 Place Jussieu, 75005 Paris, France*
[5]*Nordita, Stockholm University and KTH Royal Institute of Technology Hannes Alfvéns väg 12, 106 91 Stockholm, Sweden*
[6]*Max–Planck–Institut für Physik, Werner–Heisenberg–Institut, 80805 München, Germany*
[7]*Arnold Sommerfeld Center for Theoretical Physics Ludwig-Maximilians-Universität München, 80333 München, Germany*

We show that experiments at the Forward Physics Facility, planned to operate near the ATLAS interaction point during the LHC high-luminosity era, will be able to probe predictions of Little String Theory by searching for anomalous $U(1)$ gauge bosons living in the bulk. The interaction of the abelian broken gauge symmetry with the Standard Model is generated at the one-loop level through kinetic mixing with the photon. Gauge invariant generation of mass for the $U(1)$ gauge boson proceeds via the Higgs mechanism in spontaneous symmetry breaking, or else through anomaly-cancellation appealing to Stückelberg-mass terms. We demonstrate that FASER2 will be able to probe string scales over roughly two orders of magnitude: $10^5 \lesssim M_s/\text{TeV} \lesssim 10^7$.

arXiv:2204.06469v1 [hep-ph] 13 Apr 2022

In Ref. [1] we investigated the sensitivity of dark matter direct detection experiments to extremely weakly coupled extra $U(1)$ gauge symmetries which are ubiquitous in D-brane string compactifications [2, 3]. In this addendum to the dark matter work we particularize our investigation to experiments planned to operate at the HL-LHC Forward Physics Facility (FPF) [4, 5]. Before proceeding, we pause to stress that our investigation will be framed within the context of Little String Theory (LST), which allows us to take the string coupling g_s of arbitrary small values [6, 7]. This contrasts with previous literature on hidden $U(1)$ in string theory, which pivots on the volume of the internal space rather than on g_s.

We focus attention on the FPF’s second generation ForwArd Search ExpeRiment (FASER2).[1] FASER2 will be shielded from the ATLAS interaction point by 200 m of concrete and rock, creating an extremely low-background environment for searches of long-lived particles traveling unscathed along the beam collision axis. Herein, we are interested in searches for light, very weakly-interacting vector fields that couple through kinetic mixing to the hypercharge gauge boson or, at low energies, effectively to the Standard Model photon (SM). At hadron colliders like the LHC, dark $U(1)_X$ gauge bosons of mass m_X can be abundantly produced through proton bremsstrahlung or via the decay of heavy mesons. Indeed, over the lifetime of the HL-LHC there will be 4×10^{17} neutral pions, 6×10^{16} η mesons, 2×10^{15} D mesons, and 10^{13} B mesons produced in the direction of FASER2. The $U(1)_X$ discovery potential of FASER2 in the $(m_X, g_{X,\text{eff}})$ plane is shown in Fig. 1, where we have defined the effective kinetic mixing parameter $g_{X,\text{eff}} \equiv e\epsilon_{\gamma X}$, and where e is the elementary charge and $\epsilon_{\gamma X}$ is the physical kinetic mixing parameter. We note in passing that complementary measurements of weakly coupled $U(1)$ gauge bosons could be carried out by the proposed LHC experiments SHiP [14], FACET [15], and MATHUSLA [16].

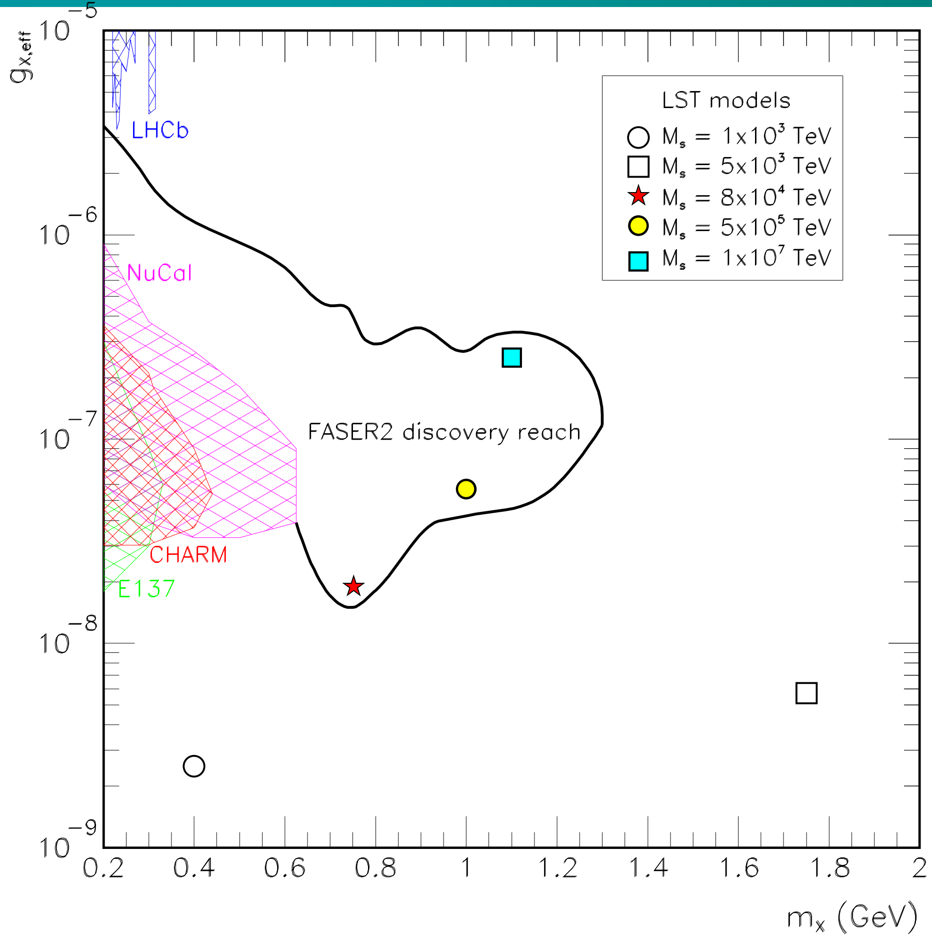
FIG. 1: Dark $U(1)_X$ sensitivity reach contour in the $(m_X, g_{X,\text{eff}})$ plane obtained with the `FORSEE` package [9]. The shaded regions are excluded by previous experiments: SLAC (E137) [10], CHARM [11], NuCal [12], and LHCb [13]. The symbols indicate particular predictions of LST models for feasible parameters given in Table I.

We now turn to demonstrate that LST provides a compelling framework for engineering very weak extra gauge symmetries with masses $500 < m_X/\text{MeV} < 800$ and $10^{-8} < g_{X,\text{eff}} < 10^{-7}$. The SM gauge group is localized on Neuveu-Schwarz (NS) branes (dual to the D-branes). However, the $U(1)_X$ gauge field could live in the bulk and if so its four-dimensional gauge coupling becomes infinitesimally small [17].

---

[1] FASER has been already installed in the LHC tunnel and will collect data during Run 3 [8].

FPF sensitivity contour for Z’:



At the end I like to show some pictures.


POUR LE VOISINAGE
SILENCE
FUMEZ

Many thanks to you Ignatios for your important contributions to theoretical physics and for the pleasant and fruitful collaboration !!

Thank you for your attention!