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

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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: $10^5 \lesssim M_s/\text{TeV} \lesssim 10^7$.

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 follow up 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

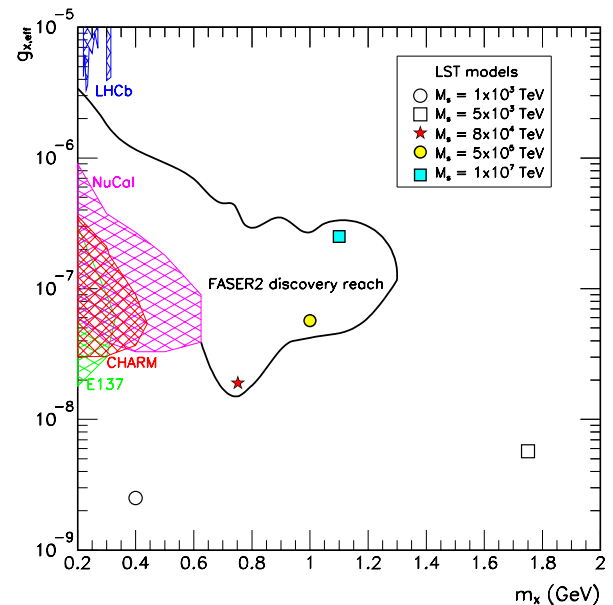


FIG. 1: Dark $U(1)_X$ sensitivity reach contour in the $(m_X, g_{X,\text{eff}})$ plane obtained with the FORSEE package [9]. The shaded regions are excluded by previous experiments: SLAC (E137) [10], CHARM [11], NuCal [12], and LHCb [13]. The symbols indicate particular predictions of LST models for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

of weakly coupled $U(1)$ gauge bosons could be carried out by the proposed CERN experiments SHiP [14], FACET [15], and MATHUSLA [16].

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 Neveu-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].

We consider a compactification on a six-dimensional space with the Planck mass given by

$$M_{\text{Pl}}^2 = \frac{8}{g_s^2} M_s^8 \frac{V_2 V_4}{(2\pi)^6} \quad (1)$$

(up to a factor 2 in the absence of an orientifold), where M_s is the string scale and we have taken the internal space to be a product of a two-dimensional space, of volume V_2 , times a four-dimensional compact space, of volume V_4 . We further consider that the SM degrees of freedom emerge on a stack of NS5-branes wrapping the two-cycle of volume V_2 . For simplicity, we assume that the internal space is characterized by a torus made of two orthogonal circles with radii R_1 and R_2 . The corresponding (tree-level) gauge coupling is given by:

$$g_{\text{SM}}^2 = \frac{R_1}{R_2} \quad (\text{Type IIA}) \quad \text{and} \quad g_{\text{SM}}^2 = \frac{1}{R_1 R_2 M_s^2} \quad (\text{Type IIB}); \quad (2)$$

hence, an order one SM coupling imposes $R_1 \simeq R_2 \simeq M_s^{-1}$. The $U(1)_X$ gauge field lives on a $D(3 + \delta_X)$ -brane that wraps a δ_X -cycle of volume V_X , while its remaining four dimensions extend into the uncompactified space-time. The corresponding gauge coupling is given by,

$$g_X^2 = \frac{(2\pi)^{\delta_X+1} g_s}{V_X M_s^{\delta_X}}, \quad (3)$$

If $U(1)_X$ arises from a D7-brane (3) can be recast as

$$g_X^2 = \frac{(2\pi)^5 g_s}{V_4 M_s^4}. \quad (4)$$

We further assume that all the internal space radii are of the order of the string length, $M_s^6 V_2 V_4 \simeq (2\pi)^6$, so that (1) and (4) yield,

$$g_X \simeq 32^{1/4} \sqrt{\pi} \sqrt{\frac{M_s}{M_{\text{Pl}}}}. \quad (5)$$

The dark gauge boson acquires a mass through the Higgs mechanism, with v_X the vacuum expectation value for the Higgs h_X that breaks the $U(1)_X$ symmetry. We consider the simplest quartic potential $-\mu_X^2 h_X^2 + \lambda_X h_X^4$, which gives $v_X = \mu_X / \sqrt{2\lambda_X}$, a Higgs mass of order μ_X , and a mass for the dark gauge boson

$$m_X = \frac{g_X \mu_X}{\sqrt{2\lambda_X}} = \sqrt{2\pi g_s} \left(\frac{8}{g_s^2} \right)^{\delta_X/2d} \left(\frac{M_s}{M_{\text{Pl}}} \right)^{\delta_X/d} v_X, \quad (6)$$

where we have taken λ_X to be $\mathcal{O}(1)$, and where d is the total number of dimensions that are large. Throughout our calculations we take $d = \delta_X$.

Alternatively, the abelian gauge field $U(1)_X$ could acquire a mass via a Stückelberg mechanism as a consequence of a Green-Schwarz (GS) anomaly cancellation [18, 19], which is achieved through the coupling of twisted Ramond-Ramond

axions [20, 21]. The mass of the anomalous $U(1)_X$ can be unambiguously calculated through a direct one-loop string computation, and is given by

$$m_X = \kappa \sqrt{\frac{V_a M_s^2}{V_X M_s^\delta}} M_s = \frac{\kappa}{(2\pi)^{\frac{\delta_X-2}{2}}} \left(\frac{\sqrt{8} M_s}{g_s M_{\text{Pl}}} \right)^{\frac{\delta_X-\delta_a}{d}} M_s, \quad (7)$$

where κ is the GS anomaly coefficient (which is a numerical factor of order 10^{-1} to 10^{-2} times $\sqrt{g_s} \propto g_X$), V_a is the two-dimensional internal volume corresponding to the propagation of the axion field [17] and δ_a is the number of large dimensions in V_a .² To develop some sense for the orders of magnitude involved, in our calculations we take $\delta_a = 2$ and $\delta_X = d = 4$. With this in mind, (7) can be rewritten as

$$m_X = \frac{\kappa}{(2\pi)} \left(\frac{\sqrt{8} M_s}{g_s M_{\text{Pl}}} \right)^{\frac{1}{2}} M_s. \quad (8)$$

For a concrete example of this set up, we envision 2 D7-branes intersecting in two common directions; *viz.*, $D7_1 : 1234$ and $D7_2 : 1256$, where 123456 denote the internal six directions. Next, we take 1234 to be large and 56 to be small (i.e, order the string scale) compact dimensions. The gauge fields of $D7_1$ have a suppression of their coupling by the 4-dimensional internal volume V_X while the states in the intersection of the two D7 branes only see the 12 large dimensions and lead to 6 dimensional anomalies, which are cancelled by an axion living in the same intersection, so V_a is the volume of 12 only.

As noted above, the $U(1)_X$ does not couple directly to the visible sector, but does it via kinetic mixing with ordinary photons. This coupling can be generated by non-renormalizable operators, but it is natural to assume that it is generated by loops of states carrying charges $(q^{(i)}, q_X^{(i)})$ under the two $U(1)$'s and having masses m_i :

$$\epsilon_{\gamma X} = \frac{e g_X}{16\pi^2} \sum_i q^{(i)} q_X^{(i)} \ln \frac{m_i^2}{\mu^2} \equiv \frac{e g_X}{16\pi^2} C_{\text{Log}} \quad (9)$$

where μ^2 denotes the renormalization scale (which in string theory is replaced by M_s), and where we absorbed also the constant contribution. The effective coupling to SM is then given by

$$g_{X,\text{eff}} = e \epsilon_{\gamma X} = \frac{\alpha_{\text{em}} g_X}{4\pi} C_{\text{Log}}. \quad (10)$$

Using (5) and (6), as well as (8) or (10) we scan over the LST parameter space. Our results are encapsulated in Fig. 1, where we show representative values of the $(m_X, g_{X,\text{eff}})$ plane, with LST model parameters listed in Table I. In our calculations we set $C_{\text{Log}} \sim 3$ [22]. A point worth noting at this

² Note that the $U(1)$ is not necessarily anomalous in four dimensions. A mass can be generated for a non-anomalous $U(1)$ by a six-dimensional (6d) GS term associated to a 6d anomaly cancellation in a sector of the theory.

TABLE I: Selected LST model parameters of points shown in Fig. 1.

Symbol	M_s (TeV)	g_s	v_X/M_s	\varkappa
○	1×10^3	2.4×10^{-13}	3.4×10^{-1}	2.6×10^{-6}
□	5×10^3	1.2×10^{-12}	1.3×10^{-1}	2.3×10^{-6}
★	8×10^4	1.9×10^{-11}	8.7×10^{-4}	5.8×10^{-8}
●	5×10^5	1.2×10^{-10}	7.5×10^{-5}	1.3×10^{-8}
■	1×10^7	2.4×10^{-9}	9.4×10^{-7}	–

juncture is that for $g_{X,\text{eff}} \gtrsim 5 \times 10^{-8}$, the associated abelian gauge boson can only acquire a mass via the Higgs mechanism, since the required GS numerical factor becomes unnaturally small. We can explicitly see in the figure that the LST parameter space region probable by FASER2 spans roughly two orders of magnitude in the string scale.

In summary, we have shown that FASER2 will be able to probe a region of the LST parameter space by searching for abelian gauge bosons living in the bulk. From (6) we see that the effective coupling $g_{X,\text{eff}}$ depends on the product $\sqrt{M_s} \times C_{\text{Log}}$. Similar $\mathcal{O}(1)$ logarithmic terms appear when computing threshold corrections to gauge couplings. For C_{Log} of order one, we can see in Fig. 1 that there is a minimum value of the string scale, roughly of order 10^5 TeV, which is in the FASER2 probable region. There is also a maximum value that can be tested in this region, $M_s \lesssim 10^7$ TeV. For the mass of the hidden Higgs, one needs some hierarchy given by v_X/M_s as shown in Table I. Given these considerations, the mass of the hidden $U(1)_X$ scales as $(v_X/M_s) \times M_s^{3/2}$, so the hierarchy increases as $M_s^{3/2}$ for fixed m_X .

In closing, we note that the SM singlet scalar field S would couple to the SM Higgs doublet H , yielding a portal into the dark sector [23]. However, for $\mu_X \gg m_H$, the $S \rightleftharpoons H$ mixing angle $\ll 1$, where m_H is the Higgs mass [24]. Using the values of v_X given in Table I, it is straightforward to see that the Higgs portal does not generate additional bounds on the model and that the hidden scalar is out of the LHC reach; e.g., for $M_s \sim 8 \times 10^4$ TeV, we have $\mu_X \sim 100$ TeV.

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