Dark Matter from Extra Dimensions

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In brane-world models with low tension, massive branons are natural candidates for dark matter. The phenomenology of these WIMP-like particles is completely determined by their mass, the brane tension and, in the case of effects due to radiative corrections, by the cutoff setting the scale of validity of the branon effective theory. In this paper, we review the main constraints on branon physics coming from colliders, astrophysics and cosmological observations, and include more recent limits obtained from electroweak precision measurements.

1. Introduction

In brane-world (BW) models, the possibility that the gravity scale is much lower than the Planck scale and possibly close to the TeV range can give rise to interesting observable effects at present or near experiments [1]. The main idea that defines the BW scenario is that the Standard Model (SM) particles are restricted to a three-dimensional hypersurface or 3-brane, whereas the gravitons can propagate along the whole bulk space.

Since rigid objects do not exist in relativistic theories, it is clear that brane fluctuations must play an important role in this framework [2]. This fact turns out to be particularly true when the brane tension scale f ($\tau = f^4$ being the brane tension) is much smaller than the D dimensional or fundamental gravitational scale M_D, i.e. $f << M_D$. In this case the only relevant low-energy modes of the BW scenarios are the SM particles and branons which are the quantized brane oscillations. Indeed branons can be understood as the (pseudo-)Goldstone bosons corresponding to the spontaneous breaking of translational invariance in the bulk space produced by the presence of the brane.

The branon properties allow to solve some of the problems of the brane-world scenarios such as the divergent virtual contributions from the Kaluza-Klein tower at the tree level or non-unitarity of the graviton production cross-sections [3]. The SM-branon low-energy effective Lagrangian reads [2, 4, 5]:

$$\mathcal{L}_{Br} = \frac{1}{2}g^{\mu\nu}\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - \frac{1}{2}M^2\pi^\alpha\pi^\alpha$$
$$+ \frac{1}{8f^4}(4\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - M^2\pi^\alpha\pi^\alpha g_{\mu\nu})T_{SM}^{\mu\nu} \quad (1)$$

We see that branons interact by pairs with the SM energy-momentum tensor. This means that they are stable particles. On the other hand, their couplings are suppressed by the brane tension f^4, i.e. they are weakly interacting. These features make them natural dark matter [6, 7] candidates (see [8] for updated reviews on cosmology and dark matter).

2. Branon signals in colliders

The branon signals in colliders depend on their number N, the brane tension scale f, and their masses M. From the effective action given in the Equation (1), one can calculate the relevant cross-sections for different branon searches. The single photon channel and the monojet production are the more interesting ones. The main results in relation with this analysis
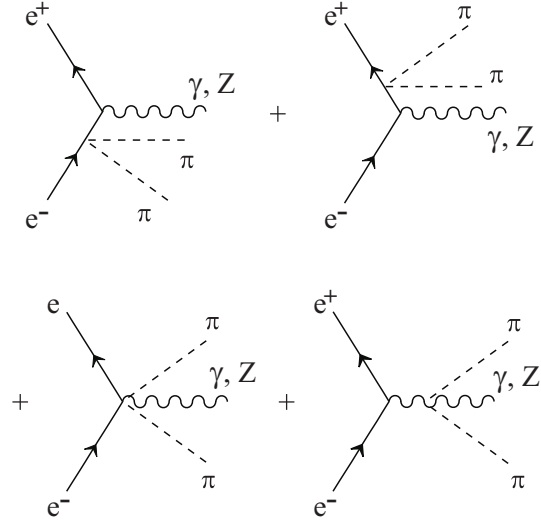

Figure 1: Relevant Feynman diagrams for the branon contribution to the single Z and the single photon channel.

are presented in Table I, where one can find not only the present restrictions coming from HERA, Tevatron and LEP-II but also the prospects for future colliders like ILC, LHC or CLIC [5, 9].

3. One loop effects

In addition to direct production and the corresponding missing energy signatures, branons can also give rise to new effects through radiative corrections.

Experiment	$\sqrt{s}$(TeV)	$\mathcal{L}$(pb^{-1})	f_0(GeV)	M_0(GeV)
HERA [1]	0.3	110	16	152
Tevatron-I [1]	1.8	78	157	822
Tevatron-I [2]	1.8	87	148	872
LEP-II [2]	0.2	600	180	103
Tevatron-II [1]	2.0	10^3	256	902
Tevatron-II [2]	2.0	10^3	240	952
ILC [2]	0.5	$2\,10^5$	400	250
LHC [1]	14	10^5	1075	6481
LHC [2]	14	10^5	797	6781
CLIC [2]	5	10^6	2640	2500

Table I Summary of the main analysis related to collider experiments. All the results are performed at the 95 % c.l. Two different channels have been studied: the one marked with an upper index [1] is related to monojet production, whereas the single photon is labelled with an upper index [2]. The table contains a total of seven experiments: HERA, LEP-II, the I and II Tevatron runs, ILC, LHC and CLIC. Obviously the data corresponding to the four last experiments are estimations, whereas the first three analysis have been performed with real data. $\sqrt{s}$ is the center of mass energy associated to the total process; $\mathcal{L}$ is the total integrated luminosity; f_0, the bound in the brane tension scale for one massless branon ($N = 1$) and M_0 the limit on the branon mass for $f = 0$.

By integrating out the branon fields in the action coming from $\mathcal{L}_{Br}$ it is possible to obtain an effective action for the SM particles which includes the effect produced by branon loops. At the level of two-point functions, branon loops result only in a renormalization of the SM particle masses which is not observable. However new couplings appear which can be described by an effective lagrangian [10] whose more relevant terms are:

$$\mathcal{L}_{eff} = W_1 T_{\mu\nu} T^{\mu\nu} + W_2 T_\mu^\mu T_\nu^\nu. \qquad (2)$$

where $T^{\mu\nu} \equiv T^{\mu\nu}_{SM}$ and

$$W_1 = \frac{N\Lambda^4}{96(4\pi)^2 f^8}$$
$$W_2 = \frac{N\Lambda^4}{192(4\pi)^2 f^8} \qquad (3)$$

for $\Lambda >> M$, Λ being the cutoff setting the limit of validity on the effective description of branon and SM dynamics used here. This new parameter appears when dealing with branon radiative corrections since the lagrangian in (1) is not renormalizable. When the branon mass M is not small compared with Λ, W_1 and W_2 have much more involved definitions, which will be given elsewhere [10].

An effective lagrangian similar to the one in (2) was obtained in [11, 12] by integrating at the tree level the Kaluza-Klein modes of gravitons propagating in the bulk and some of its phenomenological consequences

Experiment	Process	$f^2/(\Lambda N^{1/4})$ GeV
LEP combined [13]	$\gamma\gamma$	59
LEP combined [14]	e^+e^-	75
H1 [15]	e^+p and e^-p	47
ZEUS [16]	e^+p and e^-p	46
DØ [17]	e^+e^- and $\gamma\gamma$	69
CDF [18]	e^+e^- and $\gamma\gamma$	55
combined		81

Table II Estimated lower limits on $f^2/(N^{1/4}\Lambda)$ (in GeV) provided from different experiments.

where studied there. Thus it is easy to translate some of the results from these references to the present context. For example one of the most relevant contributions of branon loops to the SM particle phenomenology could be the four-fermion interactions appearing in (2) (see Figure 2) or fermion pair annihilation into two gauge bosons.
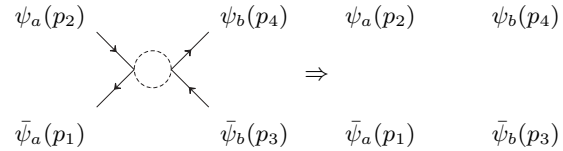

Figure 2: Four-fermion vertex induced by branon radiative corrections.

Following [19] it is possible to use the data coming from LEP, HERA and Tevatron on this kind of processes to set bounds on the parameter combination $f^2/(\Lambda N^{1/4})$. The results are shown in Table II. It is interesting to see that the various constraints found are not too different.

In a similar way, using the analysis in [20], it is possible to estimate the constraints that could be found in the next generation of colliders. For that purpose, we have taken into account the estimations calculated by Hewett for future linear colliders like the ILC, the Tevatron run II and the LHC (see Table III).

4. Electroweak precision observables and anomalous magnetic moment

Electroweak precision measurements are very useful to constrain models of new physics. The so called oblique corrections (the ones corresponding to the W, Z and γ two-point functions) use to be described in terms of the S, T, U [21] or the ϵ_1, ϵ_2 and ϵ_3 parameters [22]. The first order correction coming from the

	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (fb^{-1})	$f^2/(N^{1/4}\Lambda)$
ILC	0.5	75	216
	0.5	500	261
	1.0	200	421
Tevatron II	1.8	0.11	63
	2.0	2	83
	2.0	30	108
LHC	14	10	332
	14	100	383

Table III Estimated constraints on the parameter $f^2/(\Lambda N^{1/4})$ in GeV for some future colliders.

Kaluza-Klein gravitons in the ADD models for rigid branes to the parameter:

$$\bar{\epsilon} \equiv \frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2} \qquad (4)$$

was computed in [23]. Translating this result to our context as in the previous section we find:

$$\delta\bar{\epsilon} \simeq \frac{5\,(M_Z^2 - M_W^2)}{12\,(4\pi)^4}\frac{N\Lambda^6}{f^8} \qquad (5)$$

The experimental value of $\bar{\epsilon}$ obtained from LEP [24] is $\bar{\epsilon} = (1.27 \pm 0.16) \times 10^{-2}$. This value is consistent with the SM prediction for a light higgs $m_H \leq 237$ GeV at 95 % c.l. On the other hand, the theoretical uncertainties are one order of magnitud smaller [22] and therefore, we can estimate the constraints for the branon contribution at 95 % c.l. as $|\delta\bar{\epsilon}| \leq 3.2 \times 10^{-3}$. Thus it is possible to set the bound:

$$\frac{f^4}{N^{1/2}\Lambda^3} \geq 3.1 \text{ GeV } (\,95\,\%\,c.l.\,) \qquad (6)$$

This result has a stronger dependence on Λ (Λ^6) than the interference cross section between the branon and SM interactions (Λ^4). Therefore, the constraints coming from this analysis are complementary to the previous ones.

A further constraint to the branon parameters can be obtained from the μ anomalous magnetic moment. The first branon contribution to this parameter can be obtained from a one loop computation with the lagrangian given by (2).

The result for the KK graviton tower was first calculated by [25] and confirmed by [23] in a different way and can be written as:

$$\delta a_\mu \approx \frac{2m_\mu^2\Lambda^2}{3(4\pi)^2}(11\,W_1 - 12\,W_2), \qquad (7)$$

which for the branon case can be written as:

$$\delta a_\mu \approx \frac{5\,m_\mu^2}{114\,(4\pi)^4}\frac{N\Lambda^6}{f^8}. \qquad (8)$$

This result depends on the cut-off Λ in the same way as the electroweak precision parameters. However the experimental situation is a little different. In a sequence of increasingly more precise measurements, the 821 Collaboration at the Brookhaven Alternating Gradient Syncrotron has reached a fabulous relative precision of 0.5 parts per million in the determination of $a_\mu = (g_\mu - 2)/2$ [26]. These measurements provide a stringent test not only of new physics but also to the SM. Indeed, the present result is only marginally consistent with the SM. Taking into account the e^+e^- collisions to calculate the $\pi^+\pi^-$ spectral functions, the deviation with respect to the SM prediction is at 2.6 standard deviations [27]. In particular: $\delta a_\mu \equiv a_\mu(exp) - a_\mu(SM) = (23.4 \pm 9.1) \times 10^{-10}$. Using Equation (8) we can estimate the *preferred* parameter region for branons to provide the observed difference:

$$6.0 \text{ GeV } \geq \frac{f^4}{N^{1/2}\Lambda^3} \geq 2.2 \text{ GeV } (\,95\,\%\,c.l.\,) \qquad (9)$$

We observe that the correction to the muon anomalous magnetic moment is in the right direction and that it is possible to avoid the present constraints and improve the observed experimental value by the E821 Collaboration.

There are two interesting comments related to these results. First if there is new physics in the muon anomalous magnetic moment and this new physics is due to branon radiative corrections, the phenomenology of these particles should be observed at the LHC and in a possible future ILC (see Table III). In particular, the LHC should observe an important difference in the channels: $pp \to e^+e^-$ and $pp \to \gamma\gamma$ with respect to the SM prediction. The ILC should observe the most important effect in the process: $e^+e^- \to e^+e^-$.

On the other hand, it is interesting to note that the same physics that could explain the Dark Matter content of the Universe could also explain the magnetic moment deficit of the muon. In fact, as we show below, the above branon models with $M \sim 350$ GeV or $M \sim 850$ GeV present the total non baryonic Dark Matter abundance observed by different experiments [6]. In such a case, the first branon signals at colliders would be associated to the radiative corrections analyzed in this work and not to the direct production studied in previous articles [5].

5. Cosmological and astrophysical limits

The potential WIMP nature of branons means that these new particles are natural dark matter candidates. In [6] the relic branon abundance has been calculated in two cases: either relativistic branons at freeze-out (hot-warm) or non-relativistic (cold), and assuming that the evolution of the universe is standard for $T < f$ (see Fig. 2). Furthermore, if the max-
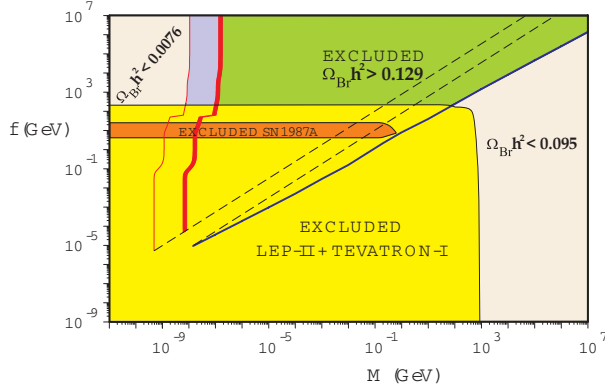
Figure 2: Relic abundance in the $f - M$ plane for a model with one branon of mass M. The two lines on the left correspond to the $\Omega_{Br}h^2 = 0.0076$ and $\Omega_{Br}h^2 = 0.129 - 0.095$ curves for hot-warm relics, whereas the right line corresponds to the latter limits for cold relics (see [6] for details). The lower area is excluded by single-photon processes at LEP-II [5] together with monojet signal at Tevatron-I [5]. The astrophysical constraints are less restrictive and they mainly come from supernova cooling by branon emission [6].

Figure 3: Elastic branon-nucleon cross section σ_n in terms of the branon mass. The thick (red) line corresponds to the $\Omega_{Br}h^2 = 0.129 - 0.095$ curve for cold branons in Fig. 2 from $N = 1$ to $N = 7$. The shaded areas are the LEP-II and Tevatron-I exclusion regions. The solid lines correspond to the current limits on the spin-independent cross section from direct detection experiments. The discontinuous lines are the projected limits for future experiments. Limits obtained from [28].

imum temperature reached in the universe is smaller than the branon freeze-out temperature, but larger than the explicit symmetry breaking scale, then branons can be considered as massless particles decoupled from the rest of matter and radiation. In such a case, branons can act as nonthermal relics and, in the particular case in which the total number of dimensions is six, it is possible to relate the cosmic coincidence problem with the existence of large extra dimensions [7].

If branons make up the galactic halo, they could be detected by direct search experiments from the energy transfer in elastic collisions with nuclei of a suitable target. From Fig. 3 we see that if branons constitute the dominant dark matter component, they could not be detected by present experiments such as DAMA, ZEPLIN 1 or EDELWEISS. However, they could be observed by future detectors such as CRESST II, CDMS or GENIUS [6].

Branons could also be detected indirectly: their annihilations in the galactic halo can give rise to pairs of photons or e^+e^- which could be detected by γ-ray telescopes such as MAGIC or GLAST or antimatter detectors (see [6] for an estimation of positron and photon fluxes from branon annihilation in AMS). Annihilation of branons trapped in the center of the sun or the earth can give rise to high-energy neutrinos which could be detectable by high-energy neutrino telescopes such as AMANDA, IceCube or ANTARES. These searches complement those already commented in high-energy particle colliders (both in e^+e^- and hadron colliders [5, 9]) in which real (see Fig. 2) and virtual branon effects could be measured [6]. Finally, quantum fluctuations of branon fields during inflation can give rise to CMB anisotropies through their direct
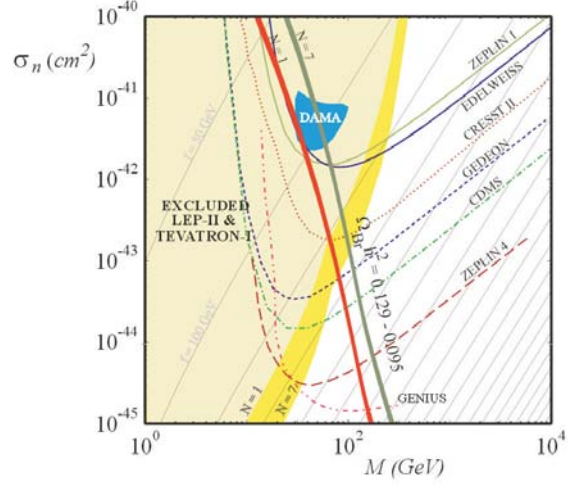
contribution to the induced metric (work is in progress in these directions).

6. Conclusions

In this paper we have reviewed the main features of branon physics. We have considered their main phenomenological signals parametrized in terms of the branon mass, the brane tension scale and the effective theory cutoff scale. At the tree level, the most important signals come from missing energy and momentum events in single photon, single Z and monojet processes in colliders. At one-loop level, the most interesting processes are those involving new four fermion interactions and finally, at the two-loop level, the electroweak precision measurements and the muon anomalous magnetic moment can also set bounds on the model parameters. We have also considered the limits coming from cosmology due to the WIMP-like nature of branons. This, in turn, ensures the existence of a relic abundance of branons, which could make up the galactic haloes.

Acknowledgments

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