

# A New Era in High-energy Physics

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## Abstract

In TeV-scale gravity, scattering of particles with center-of-mass energy of the order of a few TeV can lead to the creation of nonperturbative, extended, higher-dimensional gravitational objects: *Branes*. Neutral or charged, spinning or spinless, Einsteinian or supersymmetric, low-energy branes could dramatically change our picture of high-energy physics. Will we create branes in future particle colliders, observe them from ultra high energy cosmic rays, and discover them to be dark matter?

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We may be on the verge of a new and unexpected era in high-energy physics. Two different fundamental energy scales are observed in nature: the electroweak scale,  $E_{EW} \sim 1$  TeV, and the gravitational scale,  $E_G \sim 10^{16}$  TeV. Unification of these two scales must be encoded in any Grand Unification Theory: either the gravitational scale is lowered to the electroweak scale by some unknown physics [1], or vice versa. In the latter, nonperturbative “quantum” gravity effects become apparent at energy scales of the order  $E_G$ , whereas in the former gravitational phenomena become strong at energies sixteen orders of magnitude lower. If the fundamental scale is of the order of TeV, a collision of two particles with center-of-mass energy larger than a few TeV may lead to the formation of gravitational objects, such as black holes [2]. Nonperturbative gravitational phenomena would be observed in any physical process with energy above the TeV scale. The early universe, cosmic rays [3] and particle colliders [4] are a few examples.

String theory [5] has emerged as the most successful candidate for the theory of quantum gravity. The five consistent superstring theories and eleven-dimensional supergravity are connected by a web of duality transformations and constitute special points of a multi-dimensional moduli space of a more fundamental, nonperturbative (M-)theory. In addition to strings, nonperturbative formulation of string theory contains higher-dimensional, non-perturbative, extended objects called *branes* [6]. TeV-scale gravity can be naturally realized in string theory (see, e.g., [7]). Therefore, if string theory is the ultimate theory of nature, and the Planck scale is of the order TeV, a plethora of non-perturbative processes are possible at the TeV scale: In addition to black holes, branes will form as well. It should be noted that brane formation is a generic phenomenon that happens in any gravitational theory. The presence of a number of extra-dimensions is sufficient to allow for the existence of extended objects, though the phenomenology of the creation and decay of branes may depend on the theory. In this essay we propose that branes are created by super-Planckian scattering processes in TeV-scale gravity, and discuss some phenomenological implications of brane formation in string and Einstein theories.

A  $p$ -dimensional non-spinning extended object propagating in a  $D$ -dimensional spacetime is described by the metric

$$ds^2 = R(r)^{a_1} (-dt^2 + \delta_{ij} dy^i dy^j) + R(r)^{a_2} dr^2 + r^2 R(r)^{a_3} d\Omega_{D-p-2}^2, \quad (1)$$

where  $y_i$  ( $i, j = 1, \dots, p$ ) are the brane coordinates,  $d\Omega^2$  is the line element of the  $(D-p-2)$ -dimensional unit sphere, and

$$R(r) = 1 - \left(\frac{r_p}{r}\right)^{D-p-3}. \quad (2)$$

The explicit value of the parameters  $a_i$  depends on the underlying gravitational theory. Here, we focus on  $D$ -dimensional Einstein gravity and, motivated by M-Theory, eleven-dimensional supergravity. In the former, the parameters  $a_i$  are [8]

$$a_1 = \frac{\Delta}{p+1}, \quad a_2 = \frac{2-q-\Delta}{q-1}, \quad a_3 = \frac{1-\Delta}{q-1}, \quad (3)$$

where  $q = D - p - 2$  and

$$\Delta = \sqrt{\frac{q(p+1)}{p+q}}. \quad (4)$$

Eleven-dimensional supergravity admits an elementary/electric two-brane and a magnetic/solitonic five-brane [6]. The parameters  $a_i$  are

$$\textit{Two-brane} : \quad a_1 = 2/3, \quad a_2 = -2, \quad a_3 = 0, \quad (5)$$

$$\textit{Five-brane} : \quad a_1 = 1/3, \quad a_2 = -2, \quad a_3 = 0. \quad (6)$$

In analogy to the black hole case [2], scattering of two partons with impact parameter  $b \lesssim r_p$  produces a  $p$ -brane described by a suitable localized energy field configuration and whose exterior is described by Eq. (1). The cross section for the process depends on the brane tension and is given by the geometrical cross section corresponding to the black absorptive disk of radius  $r_p$  [8]. In fundamental units, the cross section is given by

$$\sigma_i \sim \pi r_{p,i}^2 = F_i(n, p) V_p^{-\frac{2}{n-p+1}} s^{\frac{1}{n-p+1}}. \quad (7)$$

where  $s = E_{ij}^2$  is the square of the center-of-mass energy of the two scattering partons, and  $V_p$  is the volume of the brane. The form factor  $F_i(n, p)$  depends on the model considered. For the Einsteinian brane we find

$$F_E(n, p) = \left[ \frac{64(p+1) \Gamma[(n+3-p)/2]^2}{(2+n)(n-p+2)} \right]^{\frac{1}{n-p+1}}. \quad (8)$$

The electric and magnetic supergravity branes have

$$F_{el}(n, p) = 2, \quad F_{mg}(n, p) = (2\sqrt{\pi})^{2/3}, \quad (9)$$

respectively. The total cross-section for a generic scattering process can be calculated from Eq. (7). The Large Hadron Collider (LHC) with a proton-proton center-of-mass energy of 14 TeV will possibly offer the first opportunity to observe brane formation. Assuming a fundamental Planck scale of  $M_\star = 2$  TeV, and  $D = 10$  dimensions, the total cross sections for the formation of Einsteinian branes at LHC is plotted in Fig. 1.

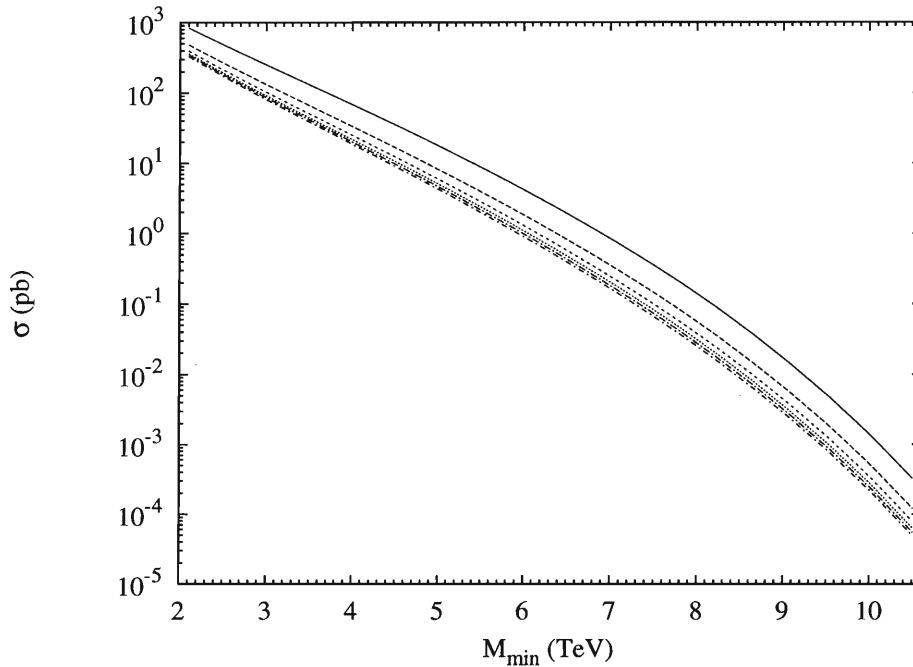


Fig. 1: Cross section (pb) for the formation of branes more massive than  $M_{\min}$  (TeV) at LHC ( $p = 0 \dots 5$  from below). The volume of the branes is assumed to be equal to one in fundamental Planck units.

For this particular choice of parameters the cross sections for brane production at LHC are in the range  $10^{-4} - 10^3$  pb. The cross section increases for increasing brane dimension. Therefore, formation of higher-dimensional branes dominates formation of lower-dimensional branes and spherically symmetric black holes (0-branes). For a minimum brane mass of  $M_{\min} = 3$  TeV, the cross section for a formation of a five- and a two-Einsteinian brane is  $\sigma_5 \approx 250$  pb and  $\sigma_2 \approx 90$  pb, respectively. Therefore, with a LHC luminosity of  $L = 3 \cdot 10^4 \text{ pb}^{-1} \text{ yr}^{-1}$  we expect a five-brane event and a two-brane event approximately every 5 and 10 seconds.

Production of branes at particle colliders - if observed - would allow to investigate the

structure of the extra-dimensions. Brane cross sections are very sensitive to the size of the brane, which is related to the size of the compactified extra dimensions around which the brane wraps. The cross section is enhanced if the length of the extra dimensions is sub-Planckian. For instance, the cross section of a five-brane wrapped on extra dimensions with size  $1/2$  of the fundamental scale is enhanced by a factor  $\approx 10$ . An enhancement of the cross section would have important consequences in high-energy cosmic ray physics, since a sufficient flux of  $p$ -branes could be detected by ground array and air fluorescence detectors [9].

We expect the creation of bosonic non-supersymmetric (non-BPS [6]) branes in particle colliders and high-energy cosmic rays. Although the decay process of a bosonic brane is not understood, string field theory suggests that a higher-dimensional brane can be seen as a lump of lower-dimensional branes [10]. The tension of the brane causes the latter to decay in lower dimensional branes, and eventually to evaporate as a black hole. Therefore, a bosonic non-supersymmetric brane can be considered as an intermediate state in the scattering process. Pursuing the analogy with particle physics, black holes can be regarded as a metastable particles and branes their resonances.<sup>1</sup>

Extremal supersymmetric branes of eleven-dimensional supergravity, however, saturate the Bogomol'ny bound, have zero entropy, and do not evaporate [11]. Therefore, if supersymmetry is unbroken and eleven-dimensional supergravity describes the physics at energies above the TeV scale, high-energy particle scattering produces stable branes (Fig. 2). In the standard cosmological scenario [12] and in the new brane-world cosmological models [13], the temperature of the early universe is expected to have reached super-TeV values: Creation of BPS branes could have been a common event in the early universe. At temperatures above the fundamental scale we expect a plasma of branes in thermal equilibrium with the primordial bath. At temperatures of the order of TeV, branes decouple from the thermal plasma, leaving stable BPS relics. Today these relics would appear to an observer like heavy supersymmetric particles with mass  $M_{br} \sim \text{TeV}$  and cross sections  $\sigma_{br} \lesssim \text{pb}$ , thus providing a candidate for dark matter. Most interestingly, a gas of branes leads to a cosmological model that solves the initial singularity and horizon problems of the standard cosmological model without relying on an inflationary phase [14].

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<sup>1</sup>We are grateful to Angela Olinto for this remark.

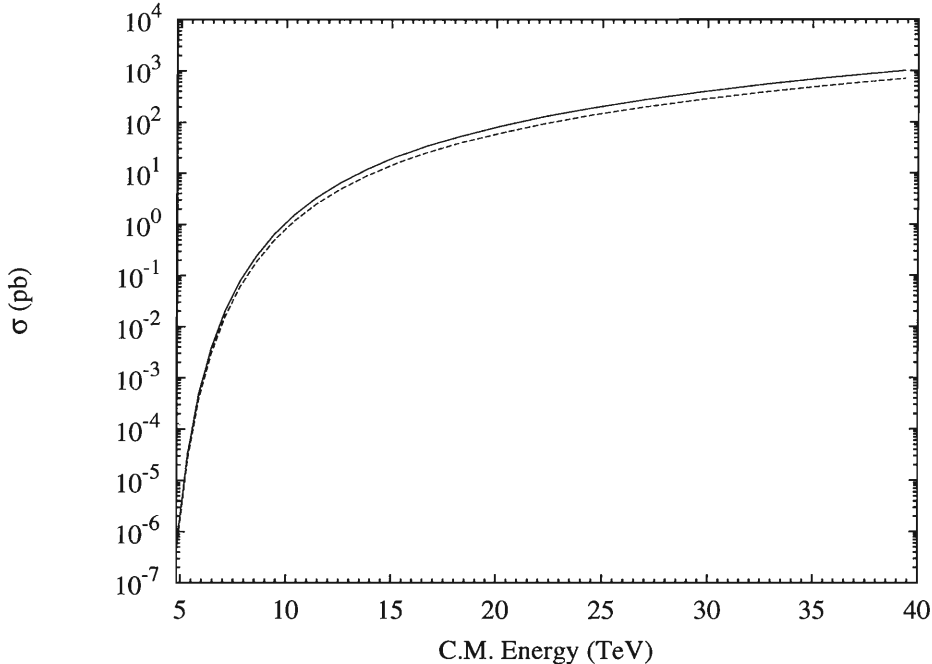


Fig. 2: Cross sections for creation of electric (lower) and magnetic (upper) supergravity branes by proton-proton scattering with  $M_\star = 2$  TeV, minimum mass  $M_{\min} = 2M_\star$ , and unit volume. The cross sections for the corresponding Einsteinian two- and five-brane are enhanced by a factor of  $\sim 2.2$  and  $\sim 2.7$ , respectively.

To conclude, in gravitational theories with large-extra dimensions creation of nonperturbative extended objects is expected to happen and have important effects on all physical processes above the TeV scale. Non-BPS brane formation in particle colliders and in the atmosphere by ultra high energy cosmic rays will probe short-distance physics and the structure of the extra dimensions. In cosmology, primordial creation of stable BPS branes may have played an important role in the dynamics of the very early universe. Brane relics could be the dark matter that is observed today. If the large-extra dimension scenario does really describes the material world and its phenomena, we may well be on the verge of a new and unexpected era in high-energy physics.

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