Search for higher dimensions through their gravitational effects in high energy collisions

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Abstract

We consider the use of a microwave parametric converter for the direct detection of gravitational effects at the LHC. Because of the extra dimensions the strength of the gravitational interaction in the bulk grows at high energies. This leads to possibly detectable signals.

The existence of additional dimensions has been widely discussed in connection with string theory [1]. It has been proposed that the extra dimensions would modify the gravitational interaction so that it becomes strong at an energy scale well below the Planck mass, possibly as low as a few TeV. Experimental signatures at the Large Hadron Collider (LHC) have been identified [2,3]. Here we speculate on the direct detection of the gravitational effects in high energy particle collisions by using an electromagnetic detector which couples directly to deformations of the space-time (3+1) metric [4].

We consider two cases and in both instances we exploit the periodic nature of the signal which is related to the collision frequency at the LHC, $f = 31.6$ MHz. In the first case we examine the deformation of the metric due to the passage of the particle bunch in the vicinity of the detector. This is a kinematic rather than a dynamic effect. In the second case we assume that during the collision, gravitational radiation is emitted into the higher dimensions (the bulk). We argue that as a consequence an “evanescent” gravitational wave is generated on the brane, and it is this disturbance of the metric that is detected [5].

1. Passage of a relativistic particle

When a fast-moving particle of mass $m$ passes by a stationary observer the metric is deformed and at closest approach, at a distance $b$, is
For details see [6]. The particle also imparts an attractive impulse on the observer (of mass $M$). In a circular accelerator the repeated passage of a bunch of $N$ particles results in an average acceleration

$$< F/M > = \frac{1}{\tau_0} \int_{-\infty}^{\infty} \frac{F(t)}{M} dt = \frac{1}{\tau_0} \frac{2Nmg}{\gamma\beta cb}(2\gamma^2\beta^2 + 1)$$

(2)

Here $\tau_0$ is the revolution period of the bunch and as before, $b$ is the distance of closest approach between the bunch and the observer.

The proposed detector is a microwave parametric converter using superconducting cavities [4,7,8]. The carrier frequency in the detector is in the GHz range, and the detection frequency can be selected at will. Such a detector can detect metric deformations of order $h_{\mu\nu} \sim 10^{-23}$ in an integrating time $\tau = 10^4$ s. Using the LHC parameters

$$N/\text{bunch} = 1.15 \times 10^{11}$$

$$\gamma = 7.461 \times 10^3$$

and $b = 0.1 \text{ m}$, Eq(1) yields $h_{oo} = 2 \times 10^{-38}$, well below the detector sensitivity.

Could this result be modified by the presence of extra dimensions? We recall that the energy scale, $M_G$, at which gravitation becomes strong is related to the Planck scale, $M_P$ through [3]

$$M_G^{D+2} = M_P^2 \left( \frac{\hbar}{Lc} \right)^D$$

(3)

Here $D$ is the number of extra dimensions and $L$ is the compactification distance. In this regime, that is at high energies and for distances $b < L$, one should replace the Newtonian constant, $G$, in Eq.(1) by $G(M_P/M_G)^2$. Thus the signal would be detectable if $M_G \sim 10^{11}$ GeV. For this value of $M_G$ the compactification distance, as given by Eq.(3), is

$$M_G = 10^{11} \text{ GeV} \quad D = 1 \quad L = 2 \times 10^{-9} \text{ cm}$$

$$D = 2 \quad L = 2 \times 10^{-17} \text{ cm}$$

(4)

These distances are much smaller than $b$, thus invalidating the above argument.
One can consider instead the currently most “popular” value for $M_G \sim 10^3$ GeV, in which case

$$M_G = 10^3 \text{ GeV} \quad D = 1 \quad L = 2 \times 10^{15} \text{ cm}$$

$$D = 2 \quad L = 0.2 \text{ cm}$$

The first of these values is excluded from experimental evidence on the validity of Newton’s law at large distances. For $D = 2$ the compactification distance is shorter than the proposed distance to the detector, $b = 10$ cm. However because of the highly relativistic motion we can argue that the (transverse?) distance $b$ is foreshortened by a factor of $\gamma$ or, as seen by the observer, the bunch passes by at a distance $\tilde{b} = b/\gamma \sim 10^{-3}$ cm.

Finally we mention that a similar experiment carried out at Fermilab using 800 GeV protons observed a signal which the authors attributed to electromagnetic background [9]. If that signal was to be interpreted in the formalism presented above it would correspond to $M_G \sim 10^9$ GeV, and a $D = 1$ compactification distance $L = 2 \times 10^{-3}$ cm.

2. Graviton emission

In this case we consider the emission of gravitons into the bulk. The cross-section depends on the energy scale where gravity becomes strong and for energetic gravitons varies in the range $1 - 10^4$ fb. [9] Assuming the upper limit and luminosity $L = 10^{34}$ cm$^{-2}$ s$^{-1}$ results in a disappointingly low rate for a resonant detector, such as we propose to use.

On the other hand, we are interested in the evanescent wave that propagates on the brane and that extends only a few wavelengths into the “wave zone”. We argue that this wave should be present for every collision and there are $\sim 20$ collisions per crossing. The frequency seen by the detector is determined by the time interval between collisions and thus fixed at $f = 36.1$ MHz.

A difficulty with the detection of high frequency gravitational waves is that for a detectable amplitude ($h_{\mu\nu}$) the energy density in the wave is very high (grows as $f^2$). This issue is not present in the case of the evanescent wave since it does not carry energy away from the interaction. The energy density in the wave that propagates in the bulk is much lower because $G$ has become strong in the extra dimensions. Thus
the proposed process is not energetically forbidden. Clearly, a numerical estimate of $h_{\mu\nu}$ is necessary in order to evaluate the feasibility of this proposal.

Here we have not addressed the problem of electromagnetic coupling to the detector and of other backgrounds. In principle such issues are manageable if a detectable signal is present.

References

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