A search for direct heffalon production using the ATLAS and CMS experiments at the Large Hadron Collider

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The first search is reported for direct heffalon production, using 23.3 fb$^{-1}$ per experiment of delivered integrated luminosity of proton-proton collisions at $\sqrt{s} = 8$ TeV from the LHC. The data were recorded with the ATLAS and the CMS detectors. Each exotic composite is assumed to be stable on the detector lifetime ($\tau \gg$ ns). A particularly striking signature is expected. No signal events are observed after event selection. The cross section for heffalon production is found to be less than 64 ab at the 95% confidence level.

I. INTRODUCTION

The high energy of the Large Hadron Collider (LHC), together with the large integrated luminosity delivered to the general purpose experiments, offers unprecedented opportunities for searches for new particles beyond the Standard Model. Given the wealth of analyses and searches that have been reported, it is perhaps surprising that to date no search has been performed for some of the more exotic composites proposed in the literature. In this paper we concentrate on the search for the heffalon, for which the LHC signature is expected to be particularly distinctive.

The heffalon is a very heavy exotic composite particle satisfying an approximate $Z_2$ symmetry. While heffalonic models differ in their details all models suggest a very large natural mass scale $M_h$, at around $4 \times 10^{30}$ GeV/$c^2$. The particle is expected to have a lifetime intermediate between that of the collider-detector scale ($\sim$ns) and the cosmological scale ($\sim$Gyr).

Cosmologically generated heffalons could have been generated in the hot, dense conditions in the early universe, however they have not yet been observed in either astronomical or cosmic ray experiments. Similarly no characteristic signature has so far been observed from annihilations in the galactic centre.

In the absence of any convincing astronomical or cosmological evidence, an LHC search is both timely and appropriate. Searches at other colliders as well as other direct detection experiments have all so far failed to find any evidence supporting the heffalon theory. As long as they continue to evade detection in collider experiments, the existence of heffalons must be considered speculative.

The production of heffalons at the LHC has a striking signature: heffalons can be expected to leave significant deposits in all detector components, even for near-threshold production. The large tracks would be distinctive and should have essentially no Standard Model background. Indeed one of the most identifiable effects of their transit through the inner detector is expected to be the characteristic loss of signal in subsequent bunch crossings over large portions of the detector volume.

We emphasise that while our results will be illustrated in terms of a particular simplified heffalon model, essentially the same analysis would apply to other exotic composites with similar masses and interaction cross sections.

II. DETECTOR AND DATA SAMPLES

The ATLAS and CMS experiments are each jumbo-sized multi-purpose particle physics detectors, each with a forward-backward symmetric cylindrical geometry and nearly 4\pi coverage in solid angle. The detectors have the usual array of pixel detectors, silicon strip detectors, large superconducting magnets, calorimeters and muon chambers. Since it is most unlikely that you are reading this section we leave the finer details to the imagination of the reader.

We note that the passage of a large-volume heffalon composite through either detector would generate significant structural deformations of the detector system. The deformations expected would be much larger than those observed during thermal cycling, so are very likely to be measurable using the detectors’ precision laser alignment systems. No attempt is made to reconstruct these ‘deformation’ signatures, which are beyond the scope of this paper, however we encourage the experimental collaborations to investigate the feasibility of identifying such signals in future dedicated analyses.

1 More details on the non-collider phenomenology are discussed in Section IV

2 It is of central importance to what follows that the reader appreciate that each experiment uses a right-handed coordinate system with its origin at the interaction point in the centre of the detector and the z-axis along the beam pipe. Cylindrical coordinates (r, \phi) are used in the transverse plane, \phi being the azimuthal angle around the beam pipe. The pseudorapidity \eta is defined in terms of the polar angle \theta by \eta = -\ln \tan(\theta/2), and the transverse energy $E_T$ by $E_T = E \sin \theta$. 

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The data samples used in this analysis were taken during the period from March to December 2012 with the LHC operating at a proton-proton centre-of-mass energy of $\sqrt{s} = 8$ TeV. It is the delivered luminosity rather than the recorded luminosity which is the more important quantity in this analysis; approximately 23.3 fb\(^{-1}\) of integrated luminosity was delivered to each experiment.

### III. HEFFALON PRODUCTION AT THE LHC

As the natural heffalonic mass scale $M_h$ is presumed to be around $4 \times 10^{36}$ GeV/c\(^2\) (7 tonnes), one might expect direct production of heffalons to be beyond the kinematic range of the LHC. However, the standard minimal heffalonic model evades this constraint by using the available centre-of-mass energy of the LHC only as a trigger to initiate the transport of pre-existing heffalons from a neighbouring brane onto ours in an extra-dimensional model.

More specifically, space-time is assumed to have $N$ small and compact extra space-like dimensions, in addition to the usual four. While all Standard Model particles are confined to a (3+1)-dimensional sub-manifold (the “SM-brane”) heffalons and gravitons are, at least in principle, able to exist at any point in the space. In practice, however, heffalons are predominantly expected to be found in only two places: either in the vicinity of the SM-brane itself, or on another sub-manifold (known as the “heffalbrane”) lying parallel to the SM-brane but displaced by a very small length scale $\sim \delta$ in one or more of the extra dimensions. The source of the confinement of the heffalons on these two branes is modelled with an effective potential having two degenerate minima (one located on each brane) separated by a potential barrier. It is the momentary lowering of this barrier caused by interactions between it and gravitons produced in the primary $pp$ collision that leads to the diffusion of heffalons from the heffalbrane onto the SM-brane and into the LHC detectors.

In short, heffalon models assert that there is a heffalon in the room, in keeping with ideas already present in the literature of the 1930s.\(^3\)

### IV. COMPATIBILITY WITH DARK MATTER AND COSMIC-RAY DATA

Heffalons have long been known to solve the dark-matter problem,\(^4\) but the long standing deficit of at-mospheric heffalons in cosmic-ray data has caused concern for proponents of the model.\(^5\) Nevertheless, it has been suggested that corrections from a quantum theory of gravity might cause the production of gravitons in collisions of SM particles to be suppressed by a warp $K$-factor

$$K(\xi, \Delta) \propto \exp \left[-(C_{\mu\nu\sigma\tau}^{\mu\nu\sigma\tau} - \xi^2)/(2\Delta^2)\right]$$

in which $C_{\mu\nu\sigma\tau}^{\mu\nu\sigma\tau}$ is the Weyl-curvature of General Relativity. The effect of a warp $K$-factor is thus to localise production of heffalons to regions of space in which the Weyl-curvature $C^2$ takes values close to the parameter $\xi$ and with a width controlled by $\Delta$. How does the Weyl-curvature vary in our vicinity of our planet? The solution of Einstein’s equations for sphere of uniform density, mass $M$ and radius $R$, has a Weyl curvature equal to zero within the sphere, and sees it fall like $1/r^6$ outside it.\(^6\)

Consequently, a value of $\xi$ near the natural value of $\xi_{\text{crit}} = 48G^2M^2/R^6$ for the earth strongly suppresses heffalon production in the upper atmosphere, on the surface of the moon, and on all cosmological objects having different values of $M^2/R^6$, while still allowing production to take place at the LHC. Whether the fine-tuning required for $\xi$ and $\Delta$ is better or worse than that associated with the SM Higgs sector is the subject of on-going research.

### V. SIMPLIFIED HEFFALON MODELS

Limits on heffalons are thus usually expressed in the simplified-model space parametrised by three parameters $\{h, T, C^2\}$. Here $h$ is the direct heffalon production cross section, $T$ is the temperature of the dark-heffalons, and $C^2$ is the square of the Weyl-curvature tensor. Our current analysis is insensitive to $T$ since our counting experiment does not measure the heffalon $pp$ spectrum which $T$ controls. Due to the location of the LHC we only present limits for $C^2 \approx 1.1 \times 10^{-10}$ s\(^{-1}\). We can however place model-independent bounds on $h$.

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\(^3\) It is going beyond observation to assert there is not an elephant in the room, for I cannot observe what is not.\(^7\)

\(^4\) The population of heffalons trapped on the heffalbrane are known as the dark-heffalons. The minimal heffalonic model predicts a mass density of dark-heffalon at $T_{\text{heff}}$ (the temperature at which the universe was last transparent to heffalons) in agreement with the recent results from Planck \(^9\). This solution of the dark matter problem is one of the strongest reasons in support of this class of heffalonic models.

\(^5\) The Tunguska incident notwithstanding.

\(^6\) Here $r$ is the standard radial co-ordinate of the (exterior) Schwarzschild metric. Note that the Weyl curvature outside a sphere of non-constant density, such as a real planet, would be smoothed out by density gradients.
VI. OBJECT AND EVENT SELECTION

The characteristic signal for direct heffalon production is a loss of signal from large areas of the detector in subsequent bunch crossings. The probability for even a low-mass heffalon to tunnel through the entire ATLAS or CMS inner detector is small; we therefore (conservatively) estimate the reconstruction efficiency to be $>99\%$. The signature is largely unaffected by acceptance issues; the probability to lose an entire heffalon composite along the beam direction, without any interaction whatever in the detection volume has been found to be negligible. We further increase our confidence in the analysis method by independently searching for loss of signal in each of the separate sub-detector layers. The event-to-event statistical correlations are fully taken into account.

Backgrounds from Standard Model processes have been modelled with the Pythia Monte Carlo program, and are found to be much smaller than one event. Backgrounds from non-collision sources have been modelled using a robust data-driven approach, the details of which can be found in our supporting documentation [10].

A representation of a heffalon candidate in the simplified detector simulation can be found in Figure 1.

VII. RESULTS AND STATISTICAL ANALYSIS

The a priori distribution of heffalon masses and spins is subject to model uncertainties, hence we employ a robust frequentist analysis for which such subjective prejudices do not play a role. We emphasise that due to the innovative event selection and reconstruction methodology, the analysis does not suffer from the effects of the nuisance parameters (e.g. jet energy scale, resolution, etc) that typically plague other, less sophisticated, studies. Other than the statistical uncertainty due to the small event count, the dominant residual uncertainty results from the luminosity uncertainty (4%).

The number of events found after full object selection can be seen in Table I, together with the expected Standard Model and non-collision backgrounds. No data-loss event is observed in any detector layer, hence it has not been possible to confirm the existence of the heffalon.

| Sub-detector | Inner | Calorimeter | Muon |
|--------------|-------|-------------|------|
| ATLAS        | Data  | 0†          | 0    | 0    |
|              | SM    | 0           | 0    | 0    |
|              | Non-collision | 0           | 0    | 0    |
| CMS          | Data  | 0           | 0    | 0    |
|              | SM    | 0           | 0    | 0    |
|              | Non-collision | 0           | 0    | 0    |

TABLE I: The number of characteristic pathological data-loss events recorded in each layer of the ATLAS and CMS detectors. († One candidate event was recorded, however it was subsequently ascribed to a cable mapping error, and hence was removed from the analysis.)

In the absence of a signal, a model-independent limit is placed on direct heffalon production. Assuming a Poisson production probability distribution, the upper limit on the production cross section is found to be $\sigma_h < 64 \text{ ab}$ at the 95% confidence level.

VIII. CONCLUSION AND OUTLOOK

The heffalon is only one of a large number of complex composite particles yet to receive verification in the collider environment. While this particular search has not yet been able to confirm the existence of the elusive heffalon, it has been able to set stringent limits on its production cross section. The forthcoming LHC energy increase is expected to further increase the heffalonic cross section and so hope remains that the question of the existence of the heffalon finally can be settled within the next few years.

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[1] A prehistoric elephant description in cave paintings from the Libian Tadrart Acacus, 12,000 B.C.: doi:10.1371/journal.pone.0049786.g002; The book of Job Ch. 40 vv 15--; De Bello Africo (40 B.C.), author unknown, commonly attributed to Julius Caesar.

[2] J. G. Saxe, The blind men and the elephant (1872); R. Kipling, Just so stories (1902); H. Aberson and H. Pearl, Dumbo the Flying Elephant (Whitman, 1941); J. de Brunhof, Histoire de Babar (1976).

[3] B. Aubert et al. (BABAR), Nucl.Instrum.Meth. A479, 1 (2002), hep-ex/0105044.

[4] C. Robin, W. T. Pooh, and Piglet, Winnie the Pooh (Methuen & Co. Ltd., 1926), chap. 5: "In which Piglet meets a Heffalump"; C. Robin, W. T. Pooh, and Piglet, The House at Pooh Corner (Methuen & Co. Ltd., 1928), chap. 3: "In which a search is organised, and Piglet nearly meets the Heffalump again".

[5] B. Alster, Proverbs of ancient Sumer : the world’s earliest proverb collection (CDL Press, 1997), ISBN 188305320X, proverb 121 5.1: “umma pi-ru-un ina ra-manisia ina bül Šankan ša kiša jātimu zú ul ibasši” [...] the elephant said to herself, ‘Among the wild creatures of Šakan, there is no one who can defecate like me’ (1900-1600 B.C.).

[6] G. Aad et al. (ATLAS), JINST 3, S08003 (2008).

[7] S. Chatrchyan et al. (CMS), JINST 3, S08004 (2008).

[8] H. M. Kallen and S. Hook, American philosophy today and tomorrow (New York: L. Furman, inc, 1935).

[9] P. A. R. Ade et al. (Planck), arXiv e-prints (2013), 1303.5062.

[10] http://secret_documents.cds.cern.ch