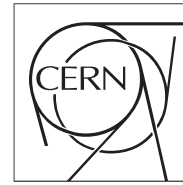


The Compact Muon Solenoid Experiment  
**Conference Report**

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# Extended Gauge Symmetries and Extra Dimensions at the Large Hadron Collider

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## Abstract

The prospects for finding signs of extended gauge symmetries and extra dimensions at the LHC are reviewed.

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# Extended Gauge Symmetries and Extra Dimensions at the Large Hadron Collider

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**Abstract.** The prospects for finding signs of extended gauge symmetries and extra dimensions at the LHC are reviewed.

## 1. Introduction

For all of the deficits of the standard model (SM) that we know about since many years – be it the non-unification of couplings at a high scale, the quadratic divergences in the loop corrections to the Higgs boson mass, or the lack of a decent dark matter candidate – a large number of solutions has been proposed. We know that within the SM, the  $W_L W_L$  scattering amplitude violates the unitarity bound at a center of mass energy  $\simeq 1.7$  TeV [1], and one solution to this problem is offered by the Higgs mechanism [2], through the introduction of a massive scalar particle. If the Higgs boson doesn't exist, some other form of new physics must be present at the TeV scale to prevent the  $W_L W_L$  scattering amplitude from violating the unitarity bound. The most popular models of new physics involve without doubt supersymmetry. However, supersymmetry doesn't explain the number of fermion generations, or their mass spectrum and charges. In this talk, sensitivity studies from the LHC experiments CMS and ATLAS for searches for manifestations of new physics are reported, in the areas of extra gauge bosons and extra dimensions.

The CERN Large Hadron Collider (LHC) is currently being installed and commissioned in the 27 km ring previously used for the LEP  $e^+e^-$  collider. This machine will push up the high energy frontier by almost one order of magnitude, providing  $pp$  collisions at  $\sqrt{s} = 14$  TeV. The luminosity for the first year of data taking, 2008, is expected to reach  $\sim 10^{32}$   $\text{cm}^{-2}\text{s}^{-1}$ , but the design luminosity is  $10^{34}$   $\text{cm}^{-2}\text{s}^{-1}$ , about a factor of 30 above the presently achieved Tevatron peak luminosity, and corresponding to an integrated luminosity of  $100 \text{ fb}^{-1}/a$ .

Both CMS and ATLAS have been designed as multi-purpose detectors capable to measure a broad range of signatures. The main difference between the experiments is the layout they have chosen for the magnet system. In ATLAS, a solenoid provides the magnetic field for the inner tracker, while a system of air-core toroids outside the calorimeters provides the field for the muon spectrometer. In CMS, the magnetic field is provided by a single large solenoid which contains both the inner tracker and the calorimeters; the muon chambers are embedded in the iron of the solenoid return yoke. The magnet layout also determines the size of the experiments.

The CMS inner detector consists of Silicon pixel and strip detectors, placed in a 4 T magnetic field. The ATLAS inner tracker is composed of a smaller number of silicon pixel and strip

<sup>1</sup> On behalf of the CMS and ATLAS collaborations

detectors and a transition radiation detector at larger radii, inside a 2 T magnetic field. The CMS electromagnetic calorimeter consists of  $\text{PbWO}_4$  crystals with excellent intrinsic energy resolution, while ATLAS chose a lead/liquid argon sampling calorimeter with worse energy resolution but a very fine lateral and longitudinal segmentation. In both detectors the hadronic calorimetry is provided by sampling detectors with scintillator or liquid argon as the active medium. The chamber stations of the CMS muon spectrometer are embedded into the iron of the solenoid return yoke, while those of ATLAS are in air. While the ATLAS toroid system is designed to provide a robust standalone muon momentum measurement, the optimal muon momentum resolution is achieved in both experiments by combining the information from the muon systems with the measurement in the inner detector. The momentum resolution for 1 TeV muons at a pseudorapidity of  $\eta = 0$  is about 7% for ATLAS and 5% for CMS.

The results shown here from the CMS experiment can be found in detail in the CMS Physics Technical Design Report Vol. 2 [3]. More information on ATLAS sensitivity studies can be found on the ATLAS exotics working group web page [4]. The studies by both experiments have reached a high level of sophistication, and while there are differences, in general the physics reach of the experiments is similar.

## 2. Extra Gauge Bosons

A possible way of resolving the inherent problems of the standard model is by extending the gauge sector of the theory. New heavy gauge bosons are predicted in many extensions of the standard model. For example, in little Higgs models, the quadratically divergent radiative corrections to the Higgs mass are canceled individually, leading to the appearance of partners of the  $W$  and  $Z$  bosons at the TeV scale. In grand unified theories heavy partners of the electroweak bosons generally appear; the left-right symmetric model is a  $SO(10)$  GUT extension of the SM, postulating the existence of a right-handed version of the weak interaction as well as an additional  $Z$  boson. Finally, the sequential standard model (SSM), where the couplings to quarks and leptons are as in the SM, serves as a good benchmark for comparisons of results.

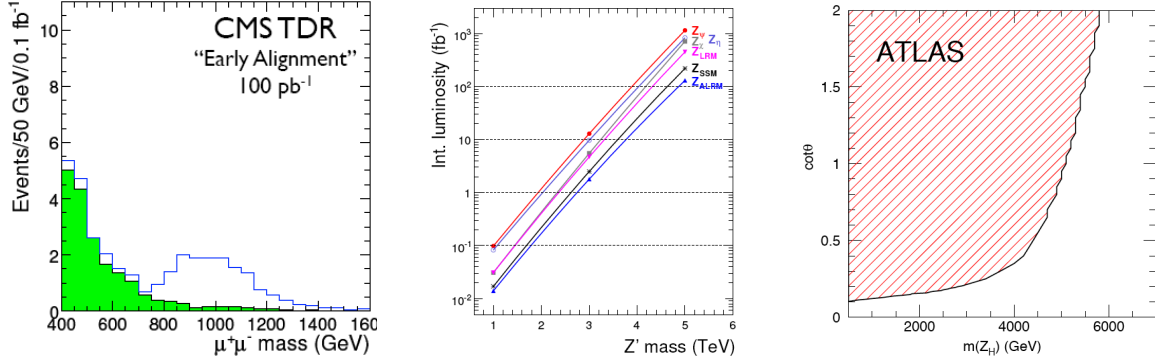
### 2.1. $Z'$

The search for  $Z'$  bosons in the di-electron and di-muon channels can be considered one of the early physics channels to be looked at at the LHC, and for this reason it has been studied in great detail. Even with small amounts of data and a detector misaligned in a way as can be expected initially (Fig. 1 (left)), a di-lepton resonance can clearly be separated from the SM background (mostly Drell-Yan production of lepton pairs) for masses above the present experimental limits from the Tevatron, which are of the order of 1 TeV. The expected discovery reach in the di-muon channel as a function of the  $Z'$  mass and the integrated luminosity for different  $Z'$  models is shown in Fig. 1 (middle). The results in the di-electron channel are comparable.

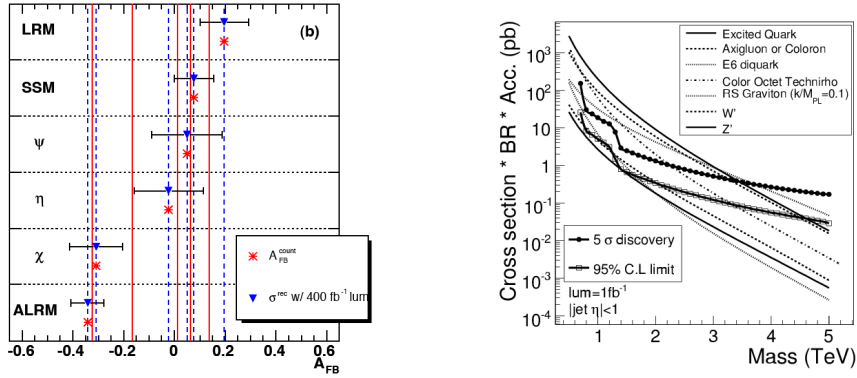
ATLAS has studied the sensitivity for the ‘‘Littlest Higgs Model’’ in different channels [5]. For example Figs. 1 (right) and 3 (right) show the expected reach for the discovery of the  $Z_H$  and  $W_H$  as a function of mass and the mixing angle between the charged vector bosons,  $\cot \theta$ , in the decay channels to  $e^+e^-$  and  $e\nu$ , respectively.

Once a new resonance has been found, one way to distinguish the different models is the measurement of the forward-backward asymmetry  $A_{FB}$  in the di-lepton center-of-mass reference frame. Even for a heavy  $Z'$  with a mass of 3 TeV, with a large integrated luminosity of  $\sim 400 \text{ fb}^{-1}$  some of the models can be discriminated (Fig. 2 (left)). For smaller masses substantially less luminosity is required.

A complementary channel to search for a  $Z'$  resonance is the di-jet channel. Although experimentally more challenging and with a smaller mass reach than di-lepton searches (see Fig. 2 (right)), the di-jet channel offers additional information and in some models is the most promising path to discovery.



**Figure 1.** (Left) Di-muon invariant mass distribution for a  $Z_\eta$  with SM background added, in a “first data” misalignment scenario. (Middle) Discovery reach ( $5\sigma$ ) for different  $Z'$  models in the di-muon channel at CMS. (Right) Discovery reach for  $Z_H \rightarrow e^+e^-$  with an integrated luminosity of  $300 \text{ fb}^{-1}$  at ATLAS.



**Figure 2.** (Left) Expected forward-backward asymmetry at CMS for a 3 TeV  $Z'$  in different models in the di-muon channel. (Right) Expected di-jet resonance discovery and exclusion reach at CMS as a function of the di-jet mass, for  $Z'$  and other resonance models.

## 2.2. $W'$

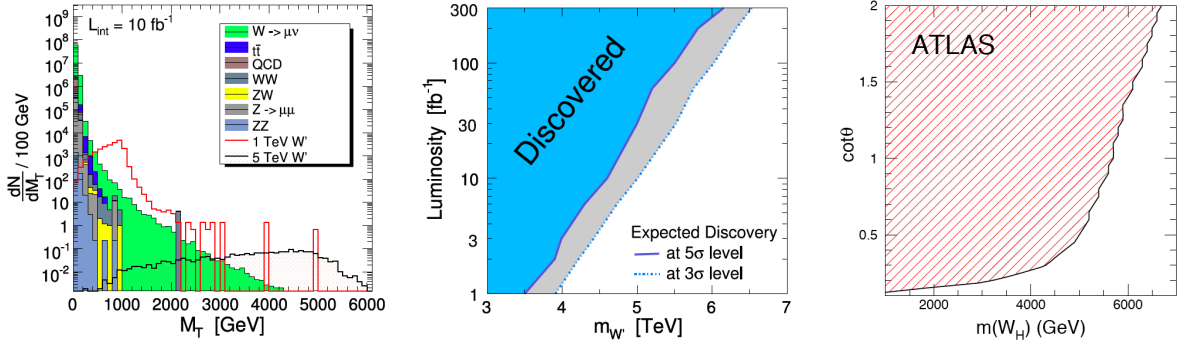
The most sensitive channel for the discovery of an additional charged gauge boson  $W'$  is the leptonic decay  $W' \rightarrow e\nu$  or  $W' \rightarrow \mu\nu$ . The reach in both channels is comparable and similar in mass to the  $Z'$  results. Fig. 3 (left) shows the transverse mass distribution in the muon plus missing transverse energy channel expected at CMS, including a hypothetical  $W'$  with a mass of 1 TeV and 5 TeV, respectively. The discovery mass reach in this channel at CMS as a function of the  $W'$  mass and the integrated luminosity is shown in Fig. 3 (middle).

## 3. Extra Dimensions

Models postulating the existence of extra spatial dimensions have been proposed to solve the hierarchy problem posed by the large difference between the Planck scale  $M_{Pl} \simeq 10^{16} \text{ TeV}$ , at which gravity is expected to become strong, and the scale of electroweak symmetry breaking,  $\simeq 1 \text{ TeV}$ .

### 3.1. Large Extra Dimensions

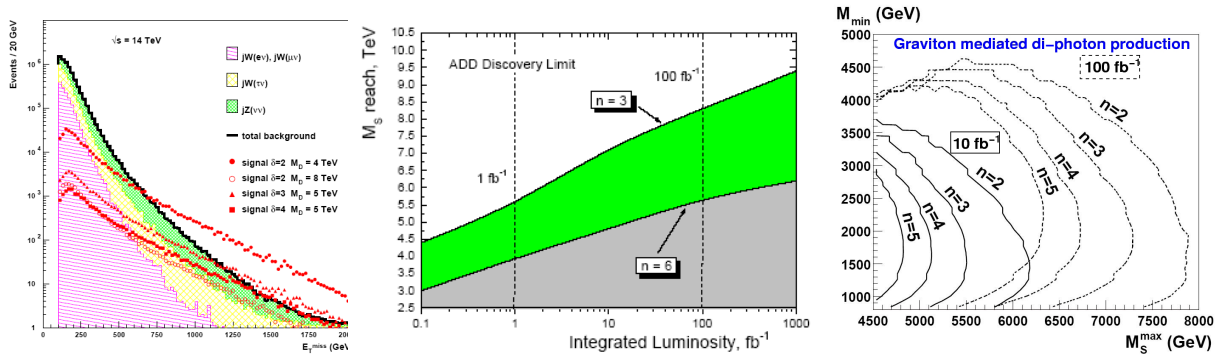
In the original large extra dimensions model of Arkani-Hamed, Dimopoulos and Dvali [6], in which only gravitons propagate in the bulk but all SM fields are confined to a 3-brane, a tower of Kaluza-Klein excitations of the graviton emerges. The graviton states are too close in mass



**Figure 3.** (Left) Transverse mass distribution in the muon plus missing transverse energy channel expected at CMS, including a hypothetical  $W'$  with a mass of 1 TeV and 5 TeV. (Middle) Corresponding discovery reach. (Right) Discovery reach for  $W_H \rightarrow e\nu$  with an integrated luminosity of  $300 \text{ fb}^{-1}$  at ATLAS.

to be distinguished individually, and the coupling remains small, but the number of accessible states is very large. It is therefore possible to produce gravitons  $G$  which immediately disappear into bulk space, leading to an excess of events with a high transverse energy jet and large missing transverse energy:  $q\bar{q} \rightarrow gG$ ,  $qg \rightarrow qG$  and  $gg \rightarrow gG$ . The dominant standard model backgrounds are the production of  $Z$  or  $W$  bosons plus jets, with the  $Z$  decaying to a pair of neutrinos or the lepton from the  $W$  decay escaping detection.

SM backgrounds and possible signals as expected in ATLAS with  $100 \text{ fb}^{-1}$  are shown in Fig. 4 (left) [7], for different values of the fundamental scale  $M_D$  and numbers of extra dimensions  $\delta$ . Other promising search channels, making use of the possibility of *virtual* graviton exchange, include di-muons (Fig. 4 (middle)), di-electrons, and di-photons (Fig. 4 (right)) [8].



**Figure 4.** (Left) Signal and background for large extra dimensions in the “monojet” channel at ATLAS with  $100 \text{ fb}^{-1}$ . (Middle) Discovery reach in the ADD model at CMS for different numbers of extra dimensions as a function of the theory scale  $M_S$ . (Right) Discovery reach in the ADD model at ATLAS in the di-photon channel;  $M_{min}$  is a lower cut-off on the di-photon invariant mass.

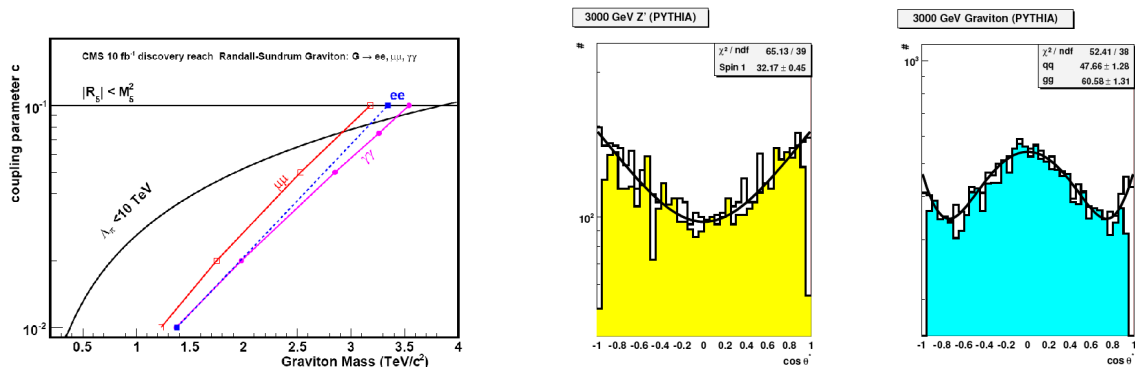
### 3.2. Randall-Sundrum Gravitons

In the model by Randall and Sundrum [9] gravity is located on a  $(3 + 1)$ -dimensional brane, the Planck brane, that is separated from the SM brane in a fifth dimension with warped metric. In the simplest version of this model gravitons are the only particles that can propagate in the extra dimension. The gravitons appear as towers of Kaluza-Klein excitations with masses and

widths determined by the parameters of the model. These parameters can be expressed in terms of the mass of the first excited mode of the graviton,  $M_1$ , and the dimensionless coupling to the SM fields,  $c = k/M_{Pl}$ . If it is light enough, the first excited graviton mode could be resonantly produced. It is expected to decay to fermion-antifermion and to di-boson pairs.

Although the branching fraction into di-photons is twice that into di-electrons or di-muons, the reach in the different channels is comparable due to the higher backgrounds when using photons. The LHC discovery reach as a function of the coupling and mass is shown in Fig. 5 (left). With  $10 \text{ fb}^{-1}$  already a large part of the theoretically preferred parameter region can be covered.

Using angular distributions, the spin 2 RS graviton could be distinguished from e.g. a spin 1  $Z'$ . Corresponding plots are shown in Fig. 5 [10]. With an integrated luminosity of  $300 \text{ fb}^{-1}$  and assuming  $c = 0.1$ , an RS graviton with a mass of 3 TeV can be distinguished from a spin 1 particle of the same mass at the  $2\sigma$  level.



**Figure 5.** (Left) Discovery reach for a Randall-Sundrum graviton at CMS in the di-lepton and di-photon channels. (Middle/right) Discrimination of a 3 TeV  $Z'$  (spin 1) and an RS graviton (spin 2) of the same mass by means of the decay angular distributions.

## 4. Conclusions

Both the ATLAS and CMS collaborations have studied in detail their respective sensitivity in searches for extra gauge bosons and extra dimensions, using final states with leptons, photons, jets, and/or missing transverse energy. Already with data from the first running period expected to take place in 2008, the reach of previous colliders will be substantially extended. It is now time to make sure the experiments are prepared for the challenges ahead.

## References

- [1] B.W. Lee, C. Quigg and H.B. Thacker, Phys. Rev. D 16 (1977) 1519.
- [2] F. Englert and R. Brout, Phys. Rev. Lett. 13 (1964) 321; P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508.
- [3] *CMS Physics Technical Design Report, Volume II: Physics Performance*, J. Phys. G: Nucl. Part. Phys. 34 (2007) 995; for information relevant to new physics searches, see also <http://cmsdoc.cern.ch/cms/PRS/results/susybsm/susybsm.html>
- [4] <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EXOTICS/>
- [5] G. Azuelos et al., Eur. Phys. J. C 39, Suppl. 2 (2005) 13, Preprint hep-ph/0402037.
- [6] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, Phys. Lett. B 429 (1998) 263 Preprint hep-ph/9803315.
- [7] L. Vacavant et al., J. Phys. G: Nucl. Part. Phys. 27 (2001) 1839
- [8] V. Kabachenko, A. Miagkovy and A. Zenin, *Sensitivity of the ATLAS detector to extra dimensions in di-photon and di-lepton production processes*, ATL-PHYS-2001-012.
- [9] L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370 Preprint hep-ph/9905221 and 4690 Preprint hep-th/9906064.
- [10] I. Belotelov et al., *Search for Randall-Sundrum graviton decay into muon pairs*, CMS Note 2006/104.