Search for Extra Space-Dimensions at the LHC

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On behalf on the ATLAS and CMS collaborations

The introduction of extra space dimensions in the theory could be an elegant way to solve the hierarchy problem. There could even be one energy scale at which all interactions could unify. The limits coming from our knowledge of the gravitation at low distance allow this energy scale to be as low as few TeV. This situation is extremely interesting experimentally in the context of the LHC which will cover the range from 100 GeV to few TeV. This article describes the different analyses developed by the LHC experiments to study this new phenomenology.

1 Motivations for Searching for Extra Space Dimensions

The Standard Model of particle physics has a very powerful prediction power but provides no answer to very important conceptual questions related to the deep structure of our universe. A part of these questions concern the relations that exist between the different interactions that we know. Are these forces originating from a unique force which would lead to a Grand Unification Theory (GUT) ? What is exactly the Plank Scale ? Is there a common framework in which all the interactions could be embedded in a self-consistent theory ? What is the exact structure of our space-time and how does it interfere with the particle spectrum that we observe ? Why do various energy scales exist in physics going from 200 GeV for the electroweak scale to 10^{19} GeV for the Plank scale ?

In the last past years, a new direction[?,?,?] has been proposed to explain why gravitation is so weak and why the Plank scale is so large. The new idea is to introduce extra-space dimensions on top of our usual 3 dimensions. These extra-dimensions are not seen at our scale, so they have to be compactified with a size smaller than the one already experimentally investigated. This size is very small for all the electroweak and strong interactions but is of the order of 0.15 mm for the gravitation[?]. So there is a possibility that these hypothetical extra-dimensions, where gravity could propagate, are quite large compactified dimensions. As a result of this situation, the usual Plank mass could be an irrelevant physical scale whereas the true gravitational scale could be much smaller, as small as few TeV.

Introducing such extra space dimensions could then solve the energy scale hierarchy or, at least, reformulate it into a geometric problem. This new framework is motivated theoretically by the fact that the only framework in which we could treat on the same bases all the interactions, including gravitation, is the string theory framework which needs extra-space dimensions for self-coherence reasons. So the question is : can we be experimentally sensitive to these hypothetical extra-dimensions ?

2 Strategy of the Searches

The main characteristics of the models of extra-dimensions is that the gravitational interaction could become non-negligible at small distances. Gravitation is brought in the field of particle physics experimentation through coupling of graviton to the usual known particles. In these models, on each vertex or on each propagator of a given model (SM, MSSM,...), one can plug a graviton leg. Having all these new vertices and the related Feynman rules, one can construct all the associated Feynman graphs for a given final state. In these models, our matter fields are bound on a 4D hypersurface of the whole (4+n)D universe while the graviton can go into the extra-dimensions (the bulk). The phenomenology is enriched when the usual gauge bosons can also propagate in the extra-dimensions. Boundary conditions that exists in the extra dimensions imply that their momentum component in the extra dimension is quantized. In our 4D world, this would be seen as the appearance of a infinite number of massive states. These so called Kaluza-Klein (KK) states are a clear experimental signal that could be observed experimentally either through their direct production or their virtual exchange contribution to standard cross-sections. Another effect of these KK states could be a modification of the renormalisation group equations, leading to possible large modifications of cross-sections. Beyond the interplay between the SM and the introduction of extra-dimensions for which the new phenomenology is already very exciting, one can also consider the modification of other, in particular SUSY, models. The LHC collaborations have studied the main models introducing extra-space dimensions. The two classes of models differ in the way they implement the space-time metric structure. The model implementing large extra-dimensions proposed by N. Arkhani-Hamed, S. Dimopoulos and G. Dvali[?] has a factorizable metric - the metric has a diagonal block structure - whereas in the Randall-Sundrum[?] there is an interplay between the (3+1)D metric and the value of the extra-dimensional coordinate. In this latter model, the dependence is exponential and is responsible for the shrinkage of the strength of the gravitational interaction in our (3+1)D subspace, often called a (3+1)-brane.

2.1 Direct Production of Gravitons

Direct production of graviton would constitute a very nice signal at the LHC. Indeed, in the simplest channels, this graviton would be produced together with a gluon, a Z boson or a photon. As the graviton interacts only gravitationally and extra dimensions are open for it, it will not interact in our detector, giving rise to a missing transverse momentum in the event. This missing E_t can be very large, much beyond 1 TeV. ATLAS has studied the graviton + jet channel[?] for which the dominant channel is $qg \longrightarrow gG$. The signal cross-section has been implemented in ISAJET using an effective theoretical approach. The generated events have been investigated

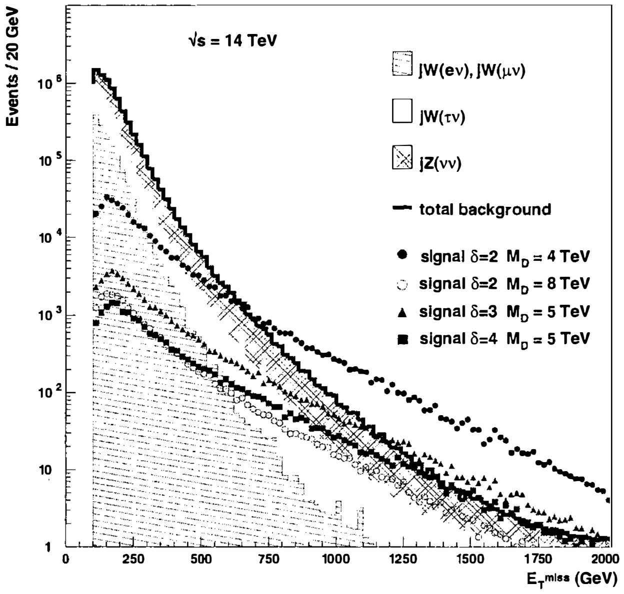

Figure 1:

using the ATLAS fast simulation program[?]. Figure ?? shows the signal shapes as detected in ATLAS as a function of the missing transverse energy for various cases of large extra-dimension model parameters and for SM distributions. This study shows that after one year of high LHC luminosity, ATLAS will be able to discover a fundamental scale up 9 to 6 TeV for 2 or 4 extra dimensions, respectively.

2.2 Virtual Exchange of Gravitons

As a quark and an antiquark annihilate into a virtual γ or Z, they can also produce a virtual graviton (or any of its KK modes). The multiplicity of KK states can give a large contribution to the production cross-section of any final state such as di-jet, di-lepton, etc. The sum of contributions to be taken into account is divergent as soon as there is more than one extra-dimension. So, in a quantum field theory framework, it has to be regularized giving rise to a low energy effective theory. This regularisation, usually done using an energy cut Λ,makes difficult to understand the exact relationship between the observable signals and the related number and scale of extra dimensions. Nevertheless, both ATLAS and CMS collaborations have studied this kind of signals, trying to understand the sensitivity of their detectors to this phenomenology. The first ATLAS study[?] focused on the channels $pp \longrightarrow l^+l^- + X$ and $pp \longrightarrow \gamma\gamma + X$. Figure ?? shows the signal shape for the two channels as a function of the two final state particles invariant mass. For a luminosity of 100 fb^{-1} (one year of LHC at high luminosity), a sensitivity to an energy scale of 7 to 8 TeV is reached for a number of extra dimensions varying between 2 and 5. A similar analysis in the di-lepton channel has been made in CMS but in the context of the Randall-Sundrum model[?]. Phenomenological constraints on this model[?] defines a "region of interest" in the ($M_{graviton}, coupling$) plane, shown in Figure ??. This figure also presents the limits that can be reached using the CMS detector both for the electronic or muonic channels.

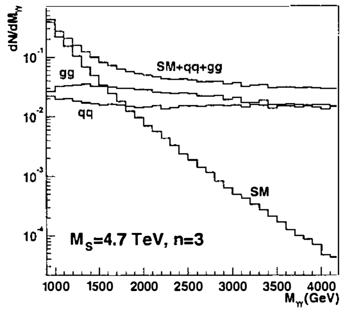

Figure 2: $pp \longrightarrow \gamma\gamma$ cross-section vs di-γ invariant mass for SM model and for 3 extra-dimensions and $M_s = 4.7$ TeV. The two contributions labeled $q\bar{q}$ or gg correspond to a graviton exchange with a $q\bar{q}$ or gg initial state.

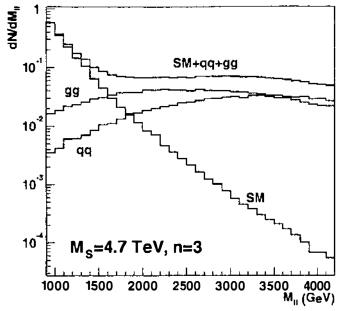

Figure 3: $pp \dashrightarrow l^+l^-$ cross-section versus the di-lepton invariant mass for SM model and for 3 extra-dimensions and $M_s = 4.7$ TeV. The two contributions labeled $q\bar{q}$ or gg correspond to a graviton exchange with a $q\bar{q}$ or gg initial state.

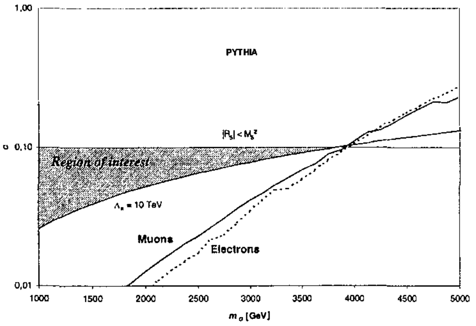

Figure 4: CMS will be able to reach on the existence of a graviton in the Randall-Sundrum model using one of the two leptonic channels e^+e^- and $\mu^+\mu^-$

The conclusion of that study is that CMS will be able to cover the whole region of interest. The ATLAS collaboration has also developed a model independent search of narrow gravitons[?] studying the di-electron production channel $gg(q\bar{q}) \longrightarrow Graviton \longrightarrow e^+e^-$. Such a resonance could be seen in the range 2 – 5 TeV in the case of the Randall-Sundrum model in the case when the coupling is the smallest allowed by the phenomenological constraints $(k/\Lambda_\pi > 0.01)$[?]. Angular distribution of polar angle of the electrons with respect to the direction of the center of mass of the pair has been performed to confirm the spin-2 property of the graviton. ATLAS will be able to distinguish a spin 2 resonance form a spin-1 resonance up to the mass of 1.7 TeV. Figure ?? shows the angular distribution expected in ATLAS for a spin-2 graviton of 1.5 TeV mass and for an integrated luminosity of 100 fb^{-1} corresponding to one year of data taking at LHC high luminosity. A solid line shows what would be the signal shape for a spin-1 resonance. ATLAS also studied the possibility to observe KK modes of the SM gauge bosons[?] if the compactification scale is of the order of few TeV. Even in absence of KK resonances, a careful study of the di-lepton cross-section can lead to a determination of the compactification scale.

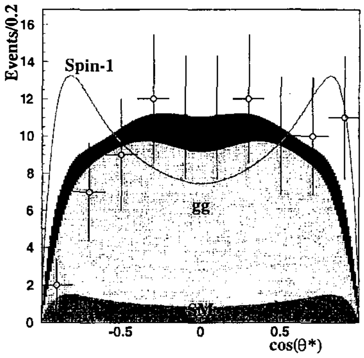

Figure 5: Center of mass frame polar angle distribution of final state electron pair direction is shown for a graviton of 1.5 TeV and for one year of LHC data at high luminosity (100 fb^-1). Solid line shows the expected signal shape for a spin-1 resonance.

2.3 Radion production in the Randall Sundrum Model

In the case of the Randall Sundrum Model, the space time metric structure is modified in a non factorizable way and we end up with the following metric :

$$ds^2 = e^{-2\mathbf{k}r_c|y|}\,\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

where r_c is the compactification radius and **k** is a number that reflects the expectation value of a field called the graviscalar Radion. A mechanism introduced by Goldberger and Wise[?] uses this field to stabilize r_c. The radion can be massive but could likely be less massive than the first Kaluza-Klein state of the graviton. The phenomenology of such a scalar is similar to that of the Higgs boson, and its existence could be confirmed by the evaluation of the decay branching ratios of the scalar field. Based on studies on the SM Higgs, limits on the observability of the radion could be obtained[?]. ATLAS has also investigated the situation where the radion would be heavier than twice the Higgs mass and studied its decay in the 2 Higgs channel for two different final states of the Higgs decay: $bb\gamma\gamma$ and $bb\tau\tau$.

2.4 Effects on the Renormalisation Group Equations

It can also happen that the extra-dimensions are open to the standard gauge bosons. In that case, it has been shown[?] that the renormalisation group equations can be modified such that the coupling evolution will be strongly altered from the standard logarithmic behavior. In such a case, unification could be obtained at a low energy scale down to few tens of TeV. ATLAS studied[?] this possibility looking at a possible suppression of di-jets production as α_s decreases quickly with the energy scale. This study was done in the framework of a large extra-dimension model. A compactification scale from 5 to 10 TeV could be reached using one year of high luminosity LHC data. Figures **??** and **??** show the significance that can be achieved in the dijet channel in ATLAS for 100 pb^{-1} and for different radii of the compactification scale or for different number of extra dimensions.

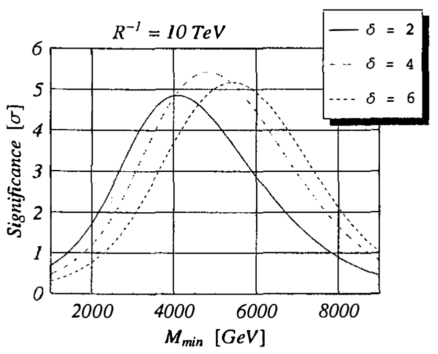

Figure 6: The statistical significance (in units of σ's) of the deviation from the Standard Model, as the function of the minimal dijet mass M_{min} at the LHC, for different numbers of dimensions and for a compactification scale of 10 TeV.

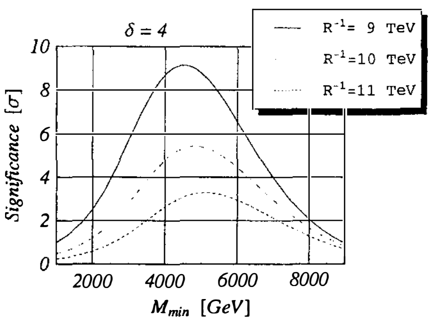

Figure 7: The statistical significance (in units of σ's) of the deviation from the Standard Model, as the function of the minimal dijet mass M_{min} at the LHC, for different compactification scales and for 4 extra dimensions.

2.5 Extra Dimensions and Supersymmetry

The existence of extra-dimensions could also have unexpected consequences. As an example, ATLAS has investigated the possibility to discover supersymmetry through the charged Higgs decay to a τ and a neutrino[7]. In the usual MSSM, the decay into a neutrino with a right helicity is strongly suppressed but this could be changed if the right-handed neutrino can go in the bulk. Indeed, conservation laws do not force the right-handed neutrino to our brane. In case where these neutrinos could go to the bulk then the phase space available for their production would enhance the charged Higgs decay width in the suppressed channel. The ATLAS analysis shows that this channel is a very good candidate to search for both extra-dimensions and SUSY.

3 Conclusion

The ATLAS and CMS collaborations have studied intensively the different models involving extra-space dimensions.It appears that the LHC experiments will be very sensitive to the related signals and should be able to either discover these dimensions or draw limits to a possible compactification scale above 5 to 10 TeV, depending on the models.

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