Monte Carlo simulations for extra dimensional models at the LHC

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The first attempts to extend general relativity to include electromagnetism date back to Theodor Kaluza (1919), Oscar Klein (1926) and other people (even Einstein).

Theories which require extra dimensions

In the last thirty years virtually any new development in theoretical physics required the introduction of extra dimensions.

- The first string revolution (*superstrings*) of the 80s translated the interest to 10D with 6D compactified spaces (Calabi-Yau, orbifolds...).
- The second string revolution (*M-theory*) of the 90s introduced new ideas such as non-perturbative strings, dualities, branes and string theories unification.

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KK–Gravitons

Gravitons in a KK–theory

When dealing with a rigid brane ($f \gg M_D$), the fact that gravitons propagate in the bulk 5D space produce a tower of KK excitations with increasing invariant mass. This mass roughly correspond to the eigen–energy of a quantum oscillator confined in the two extra dimensions.

When integrating over all the possible KK modes, we obtain an effective theory where two massive gravitons of a certain mass M_D are emitted, although actually only one graviton (with an unknown invariant mass) is emitted.

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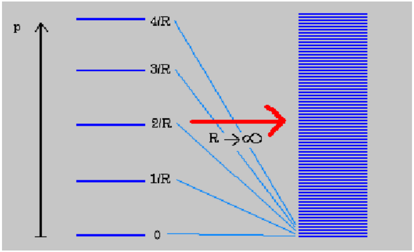

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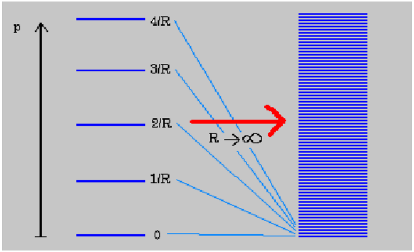

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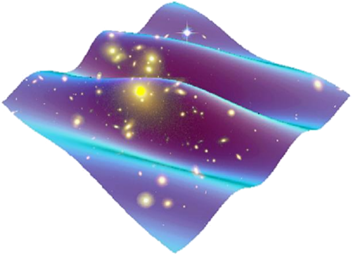

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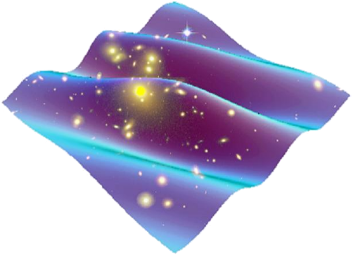

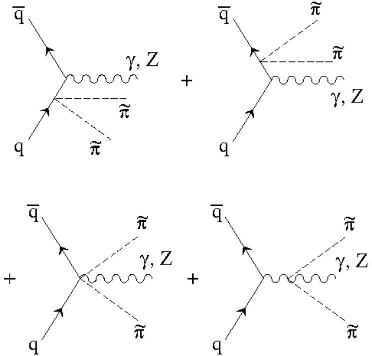

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Phenomenology

- In this work, the single photon channel is used to check both the KK–graviton an branon models.
- In particular, the KK–graviton case will be used to compare with the simulation of ref.
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KK–graviton case

For the KK–graviton case, we are looking for the channel $q\bar{q} \to \sum_n \gamma h^{(n)}$, with differential cross section

$$\frac{d\sigma(q\bar{q} \to \sum_n \gamma h^{(n)})}{dm^2 dt} =$$

$$\frac{Q_q^2 \alpha}{48 m^2 M_D^2 \hat{s}^3 tu} \left(\frac{m^2 \pi}{M_D^2}\right)^{N/2} (\hat{s} m^2 + 4tu)(2\hat{s} m^2 + t^2 + u^2)$$

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And for the branon one, we are looking for the channel $q\bar{q} \to \gamma\pi\pi$, with differential cross section

$$\frac{d\sigma(q\bar{q} \to \gamma\pi\pi)}{dk^2 dt} =$$

$$\frac{Q_q^2 \alpha N (k^2 - 4M^2)^2}{184320 f^8 \pi^2 \hat{s}^3 tu} \sqrt{1 - \frac{4M^2}{k^2}} (\hat{s}k^2 + 4tu)(2\hat{s}k^2 + t^2 + u^2)$$

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PYTHIA8

- To deal with those computations, the general MC framework PYTHIA8 has been used[1].
- The $2 \to 3$ production processes of both KK–graviton and branon models have been hardcoded within the internal phase space selection machinery of PYTHIA8.
- The multiplicative coefficients $M_D^{-2}(m^2\pi/M_D^2)^{N/2}$ for the KK–graviton and f^{-8} for the branon cases have been considered by rescaling the MC computed cross sections, thus avoiding a highly computational demanding calculation for several values of M_D and f.
- On the contrary, performing different computations for several N (KK–gravitons) and M (branons) values has been unavoidable.

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Experimental cuts

- We have tried to reproduce the cuts used by ATLAS collaboration[2] in spite of our limited knowledge of detectors.
- The fully simulated KK–graviton case has been used as a check.
- The required conditions are:
  - One isolated photon with $p_T > 150\,\mathrm{GeV}$ and $|\eta| \in [0, 1.37) \cup (1.52, 2.37)$.
  - A number of jets ≤ 1, with an anti-kT clustering algorithm with $R = 0.4\,\mathrm{GeV}$, $p_{T,min} > 30\,\mathrm{GeV}$ and $|\eta| < 4.5$.
  - Only observable final–state particles are included in the analysis. Both the high p_T photon and the hypothetical DM particles are explicitly excluded. The true masses of particles are also used.
  - In a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the photon the sum of the energies of all the visible particles is $< 5\,\mathrm{GeV}$.

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- A transverse missing momentum $E_T^{\mathrm{miss}} > 150\,\mathrm{GeV}$. To compute it, we take into account all the visible particles with $|\eta| < 4.9$.
- The reconstructed photon, transverse missing momentum and jet (if found) are separated by $\Delta\phi(\gamma, E_T^{\mathrm{miss}}) > 0.4$, $\Delta R(\gamma, \mathrm{jet}) > 0.4$ and $\Delta\phi(\mathrm{jet}, E_T^{\mathrm{miss}}) > 0.4$.
- There are neither electrons nor positrons nor muons. This restriction applies to electrons (and positrons) with $p_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.47$. And to muons with $p_t > 10\,\mathrm{GeV}$ and $|\eta| < 2.4$.
- However, in compliance with our simulations, the effect of the last restriction over the *signal* is negligible although it is expected to reduce the background.

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Experimental cuts

- As there is no signal of physics beyond SM in the ATLAS data, exclusion regions for both KK–gravitons and branons models have been computed.
- Both experimental points and simulated SM background, and their uncertainty, have been extracted from the ATLAS publication[3].
- The χ^2 value has been computed (taking $\sigma^2 = \sigma^2_{\rm data} + \sigma^2_{\rm background}$) for both the KK–gravitons and branons cases, with the ATLAS data. This computation depends on M_D and N values (KK–gravitons); and f and M values (branons).
- For KK–gravitons (branons), and different values of N (M), we have numerically computed the required value of M_D (f) for obtaining a value of χ^2 which is the maximum allowed by a 95% confident limit.

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- As there is no signal of physics beyond SM in the ATLAS data, exclusion regions for both KK–gravitons and branons models have been computed.
- Both experimental points and simulated SM background, and their uncertainty, have been extracted from the ATLAS publication[3].
- The χ^2 value has been computed (taking $\sigma^2 = \sigma^2_{\rm data} + \sigma^2_{\rm background}$) for both the KK–gravitons and branons cases, with the ATLAS data. This computation depends on M_D and N values (KK–gravitons); and f and M values (branons).
- For KK–gravitons (branons), and different values of N (M), we have numerically computed the required value of M_D (f) for obtaining a value of χ^2 which is the maximum allowed by a 95% confident limit.

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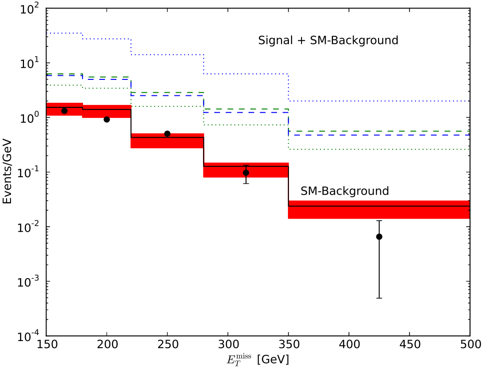
ATLAS data and theoretical models



- ATLAS data: black dots
- SM background: red band
- KK–graviton + SM back.: dashed lines
  - Lower blue: $M_D = 1\,\mathrm{TeV}$, $N = 2$
  - Upper green: $M_D = 1.5\,\mathrm{TeV}$, $N = 6$
- Branon + SM back.: dotted lines
  - Upper blue: $M = 2\,\mathrm{TeV}$, $N = 1$, $f = 60\,\mathrm{GeV}$
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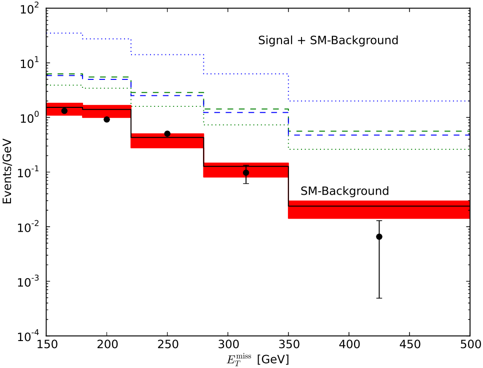

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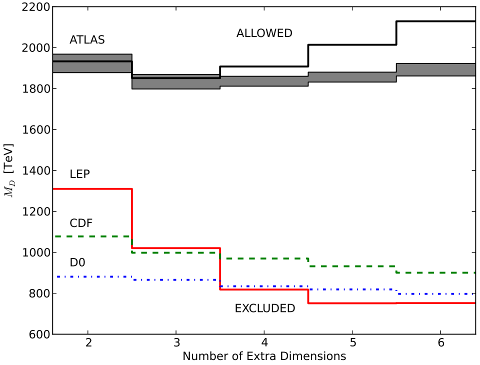

- Computed lowest limit (with ATLAS data): black line
- NLO computation of ATLAS: gray band
- LEP limit: solid red line
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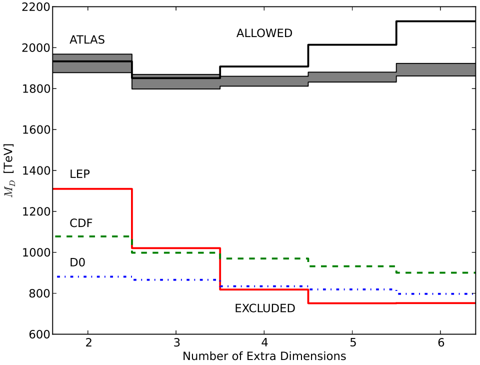

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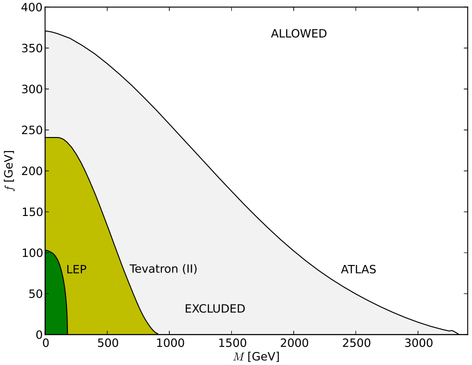
Branons



- Computed exclusion region (with ATLAS data): gray area
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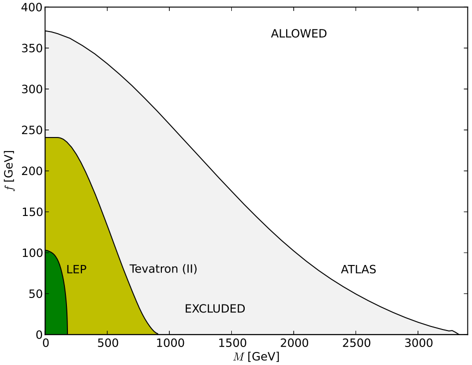

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