Extra Dimension Signatures at ATLAS

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Implications of LHC results for TeV-scale physics, August/Sept 2011, CERN
Introduction

Motivation?

• Hierarchy problem – Gravity $10^{32}$ times weaker than weak force
  • Solution: $n$ extra dimensions of size $R$, Planck Scale $M_{Pl}$
  • (Reduced) fundamental Planck Scale $M_D << M_{Pl}$

Providing a starting point for searches:

• strong constraints from electroweak precision data
  • $M_D > 2 - 5$ TeV
  • Can be circumvented by model

• Tevatron and LEP results
  • $M_D > 1.6 - 0.8$ TeV ($n = 2 - 6$)

• Non-collider bounds
  • Direct measurements: e.g. $n = 2 \rightarrow M_D > 3.2$ TeV
  • Micro Black Holes in cosmic rays:
    • $M_D > 1.0 - 1.4$ TeV ($n = 4 - 7$)
  • Cosmological constraints, if $M_D \sim$TeV, $n > 4$
    • Model dependant

Before LHC results: $M_D \sim 1$ TeV quite possible, but low $n$ disfavoured
## Three Main Classes

### ADD
Arkani-Hamed, Dimoupoulos, Dvali

**Characteristics**
- n extra dimensions only accessible to gravity
- Eliminates Hierarchy Problem

**Kaluza-Klein (KK) spectra**
- Modes with energy spacing < 1GeV
- Cant be resolved, continuum

**Searched at ATLAS include the following signal benchmarks**
- Graviton production/mono-jets
- Semi-classical black-holes, string-balls, ...
- Quantum “black holes”*

### RS model
Randall-Sundrum

**Characteristics**
- Gravitons in single ED with special metric (“warped”)
- Naturally solves hierarchy problem
- “Particle in a box”
- Distinct energy eigenvalues

**RS-graviton**
- -> dileptons,
- -> diphotons

**KK-gluon -> ttbar**
- Semi-classical black-holes, string-balls, ...
- Quantum “black holes” *

### UED
Universal Extra Dimensions

**Characteristics**
- All fields propagate in EDs, but KK-number is conserved
- Eliminates Hierarchy Problem
- Distinct energy eigenvalues
- KK-number conservation ->
  - Pair production
  - Lightest mode stable

**KK-quark/gluon pair ->**
- lightest KK pair + X ->
  - diphoton + ETmiss + X

**Semi-classical black-holes, string-balls, ...
- Quantum “black holes”**

*ADD Monte Carlo generator used as benchmark
### Three Main Classes

<table>
<thead>
<tr>
<th><strong>ADD</strong></th>
<th><strong>RS model</strong></th>
<th><strong>UED</strong></th>
</tr>
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<td>Arkani-Hamed, Dimoupolous, Dvali</td>
<td>Randall-Sundrum</td>
<td>Universal Extra Dimensions</td>
</tr>
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**Characteristics**

- ADD: n extra dimensions only accessible to gravity
- RS model: Gravitons in single ED with special metric (“warped”)
- UED: All fields propagate in EDs, but KK-number is conserved

- ADD: Eliminates Hierarchy Problem
- RS model: Naturally solves hierarchy problem
- UED: Eliminates Hierarchy Problem

**Kaluza-Klein (KK) spectra**

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**Searched at ATLAS include the following signal benchmarks**

**Graviton production/mono-jets**

- ADD: RS-Graviton
  - -> dileptons,
  - -> diphotons
- RS model: Semi-classical black-holes, string-balls, ...
  - KK-gluon -> t\(\bar{t}\)
- UED: Semi-classical black-holes, string-balls, ...

- ADD: Quantum “black holes”*
- RS model: Quantum “black holes” *
- UED: Quantum “black holes” *

**Extra dimensions/TeV Scale Gravity in ATLAS notes are:**

- **Green:** Main result
- **Purple:** Adapted result
- **Red:** Additional interpretation (analyses already presented)

*ADD Monte Carlo generator used as benchmark

**data set >1/fb**

September 1st 2011,
UED: Diphoton + MET

Model (in addition to SUSY*)

- One UED embedded in larger space with $N = 6$ additional dimensions
- Lightest KK particle = $\gamma^*$
  - Decays gravitationally to $\gamma +$ Graviton
- Only 2010 results public at the moment

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ range [GeV]</th>
<th>Data events</th>
<th>Predicted background Total</th>
<th>Expected signal events UED</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 20</td>
<td>698</td>
<td>-</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>20 - 75</td>
<td>63</td>
<td>61.4 ± 2.3</td>
<td>0.25 ± 0.02</td>
</tr>
<tr>
<td>75 - 125</td>
<td>1</td>
<td>0.38 ± 0.08</td>
<td>0.43 ± 0.02</td>
</tr>
<tr>
<td>&gt; 125</td>
<td>0</td>
<td>0.10 ± 0.04</td>
<td>5.35 ± 0.11</td>
</tr>
</tbody>
</table>

Observed 95% CLs limit

- $1/R > 961$ GeV
  ($M_D = 5$ TeV, $\Lambda R = 20$)

Tevatron (D0)

- $1/R > 477$ GeV

* see working group 2
RS: Graviton Production

Model

- Production and subsequent decay of RS graviton

Analyses:

Diphoton resonance search (2010 data only)

- Fully data driven background – fit of smooth parameterisation
- RS Graviton mass $m_G > 920 \ (545)\ GeV$ at 95% CL, for coupling $k/M_D = 0.1 \ (0.02)$

Dilepton resonances

(2011 data, combined with search for $Z'$)*

- $\mu$ and $e$ channel combined
- Data consistent with Drell-Yan production
- RS $m_G > 1.63\ TeV$ at 95% CL ($k/M_D = 0.1$)


<table>
<thead>
<tr>
<th>Model/Coupling</th>
<th>RS Graviton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.01 0.03 0.05 0.1</td>
</tr>
<tr>
<td>Mass limit [TeV]</td>
<td>0.71 1.03 1.33 1.63</td>
</tr>
</tbody>
</table>

Tevatron:

RS $m_G > 1.08\ TeV$ at 95% CL ($k/M_D = 0.1$)

* see working group 3: New fermions and gauge interactions

September 1\textsuperscript{st} 2011,
RS: KK-gluon production

Model
- Benchmark: KK-gluon decaying to ttbar in the dilepton channel

Analysis:
- Based on
  - HT: scalar sum of lepton and jet transverse momenta
  - ETmiss: scalar missing transverse momentum
- Limited by reconstruction of top decay (current analysis most sensitive up to 1 TeV)
- No evidence for new physics
- 95% CL limits depending on coupling strength (default parameter 0.2):

<table>
<thead>
<tr>
<th>$g_{qqgKK}/g_s$</th>
<th>Mass Limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.20</td>
<td>0.80</td>
</tr>
<tr>
<td>-0.25</td>
<td>0.88</td>
</tr>
<tr>
<td>-0.30</td>
<td>0.95</td>
</tr>
<tr>
<td>-0.35</td>
<td>1.02</td>
</tr>
</tbody>
</table>

sign only important if interference taken into account
Quantum Black Holes

• Used as generic term for any quantum gravitational effect resulting in low multiplicity final states

**Benchmark**: BlackMax (ADD)

• Enhancement of central dijet cross-section above a production threshold $M_{th} = M_D$

Analyses: (public results with 2010 data)

• Benchmark result from observed dijet mass $m_{jj}$ distribution:
  • $M_D > 3.67$ TeV at 95% CL ($n = 6$)

<table>
<thead>
<tr>
<th>Number of Extra Dimensions</th>
<th>$M_D$ Limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>2</td>
<td>3.20</td>
</tr>
<tr>
<td>3</td>
<td>3.38</td>
</tr>
<tr>
<td>4</td>
<td>3.51</td>
</tr>
<tr>
<td>5</td>
<td>3.60</td>
</tr>
<tr>
<td>6</td>
<td>3.67</td>
</tr>
<tr>
<td>7</td>
<td>3.73</td>
</tr>
</tbody>
</table>

• Dijet angular distributions
  • Less dependent on modelling
    • E.g. how does the production cross-section evolve in $m_{jj}$, sharp turnon, resonances, ...?
  • Use of highest mass bin $m_{jj} > 2$ TeV in distribution of $\chi = \exp(|y_1- y_2|) = (1+\cos\theta^*)/(1-\cos\theta^*)$

* see working group 3: New fermions and gauge interactions

** $y_{1,2}$: rapidities of two leading jets, $\theta^*$: cms scattering angle
Micro Black Holes

Use of semi-classical approximation
• Black hole decay via Hawking radiation
  • Democratic decay into high multiplicity of SM degrees of freedom
• Only strictly valid for $M_{th} \gg M_D$
• Signal samples produced using BlackMax generator
  • $\sigma \times A$ results can be interpreted in different contexts

Analyses: (public results with 2010 data)

Multijets
• Data driven background estimate
  • 2-D control region
  • Verified using ALPGEN and Pythia
• No evidence for production of micro black holes
• 95% CL limit on $\sigma \times A$ of 0.29pb
  • For events with $N_J \geq 5$ and $\sum p_T > 2$ TeV

Benchmark:
• ADD, $n = 6$, $M_{th} = 3 M_D$
• $M_D > 1.37$ TeV at 95% CL
Micro Black Holes

Same-Sign Dimuons

- Event selection
  - Two same-sign muon candidates, leading muon isolated
    - Signal region: Number of tracks > 9
  - Data consistent with SM prediction
  - 95% CL limit on $\sigma \times BR \times A$ of 0.184 pb
  - Interpretation in context of non-rotating and rotating micro black holes
  - Benchmark: ADD, $n = 6$, $M_{th} = 3 M_D$
    - $M_D > 1.20$ TeV at 95% CL

[ATLAS-CNF-2011-065]
**Monojet Search**

- Event selection of signal region*
  - Leading jet $p_T > 250$ GeV, $E_T^{\text{miss}} > 220$ GeV
  - No additional jet with $p_T > 60$ GeV or lepton/photon
- Background estimates data-driven or MC with data-driven normalization
- Event count in signal region consistent with SM prediction
- 95% CL limit on $\sigma \times \text{BR} \times A$ of 0.11 pb

- Interpretation in context of ADD prompt graviton production
  - $M_D > 2.0$ TeV at 95% CL, for $n = 6$

* The note provides all results for three signal regions, low to high $p_T/E_T^{\text{miss}}$. Given here is the one used for the final/benchmark results.
• LHC and ATLAS (+CMS ☺) are working well and very efficiently
  • Stringent limits on extra dimensions in many channels
    • Threshold for enhancement of dijet production > 3.2 TeV, for any \( n = 2..7 \) (with 2010 data)
      • \( M_D \) typically not expected significantly lower
    • Monojet limits on \( M_D \) from 2 to 3.2 TeV
    • Phase space for RS graviton production significantly narrowed
• New physics, and specifically strong gravity/extra-dimensions were not around the corner ☹
  • LHC no black-hole factory (none expected in 7 TeV LHC data anymore?)
• It might be time to rethink assumptions and explore different corners of the phase space
• A factor ~2 to ~50 more data available compared to the results presented

Thanks for your attention!