Bounds on large extra-dimensions from the LHC

arXiv:1101.4919

with

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Outline

- Motivation
- Phenomenology
- Bounds on tree-level graviton exchange
- Real graviton emission
- Conclusions
after all the hierarchy might be between two not so separated scales ...

This is what happens when gravity feels $D = 4 + \delta$ dimensions:

$\tilde{M}_{pl}^2 = \tilde{M}_D^{2+\delta} \cdot V(\delta)$

where $V \sim R^\delta$, $\tilde{M} \equiv M/\sqrt{8\pi}$

$R = 10^{12}, 10^{-3}, 10^{-12}, 10^{-15}$ m for $\delta = 1, 2, 4, 6$

$\frac{1}{R} = 10^{-21}$ eV, $10^{-4}$ eV, $20$ KeV, $7$ MeV for $\delta = 1, 2, 4, 6$

- KK expansions naively gives $m_{g_n} \sim \frac{n}{R}$

- astrophysics limits for gravitons below $O(100)$ MeV


- can be avoided lifting the KK tower above $O(100)$ MeV with a modification of the metric of the ED

Gravitons exchange

- KK states of the graviton tower can mediate $2 \rightarrow 2$ scattering

- Each graviton is weakly coupled, $\sim 1/M_{pl}$, but there are many KK (due to the large ED phase-space as $m_{KK} = p_{ED}$)
- The effect might be dominated by UV physics ($\delta > 2$)
- At the very least you can model the effect of tree-level exchange of gravitons with a dimension-8 operator

$$\mathcal{L} \supset c_T \mathcal{T} \equiv \frac{8}{M_T^4} \cdot \frac{1}{2} \left( T_{\mu\nu} T^{\mu\nu} + \frac{1}{\delta + 2} T_\mu^\mu T_\nu^\nu \right)$$
\( pp \rightarrow \gamma\gamma, \ell\bar{\ell}, \ldots \) and do not forget \( jj \)

**Energy pays off to probe the dim-8: LHC7@2010 \( \gg \) TeVatron**

\[
\sigma = \left( \frac{2 \text{ TeV}}{M_T} \right)^8 \times \begin{cases} 
12.5 \text{ pb} & \text{for } pp \rightarrow jj \text{ no search so far ...} \\
10.4 \text{ fb} & \text{for } pp \rightarrow \mu^+\mu^- \text{ EXO-11-039} \\
21.3 \text{ fb} & \text{for } pp \rightarrow \gamma\gamma \text{ EXO-11-038}
\end{cases}
\]

- \( \ell\bar{\ell} \) and \( \gamma\gamma \) roughly a cut-and-count in the high mass region
- \( jj \) has a larger rate, but cut-and-count is risky due to QCD uncertainties
Energy pays off to probe the dim-8: LHC7@2010 $\gg$ TeVatron

$$\sigma = \left( \frac{2\text{ TeV}}{M_T} \right)^8 \times \begin{cases} 12.5\text{ pb} & \text{for } pp \to jj \quad \text{no search so far ...} \\ 10.4\text{ fb} & \text{for } pp \to \mu^+\mu^- \quad \text{EXO-11-039} \\ 21.3\text{ fb} & \text{for } pp \to \gamma\gamma \quad \text{EXO-11-038} \end{cases}$$

- $\ell\ell$ and $\gamma\gamma$ roughly a cut-and-count in the high mass region
- $jj$ has a larger rate, but cut-and-count is risky due to QCD uncertainties

- Bounds can be extracted from the angular distribution arXiv:0906.4819 (D0)
- $uu \to uu$ dominates at LHC $\Rightarrow jj$ is even better than at TeVatron
\[
\frac{d\sigma}{d\chi} \text{ angular distribution, } \chi \equiv \exp(|y_1 - y_2|)
\]

Being the mediator a spin-2 each vertex has a \( p_T^2 \) dependence as opposed to the \( p_T \) dependence of a spin-1.

- Signal gives more central events (small \( \chi \))

\[ M_T > 3.4 \text{ TeV with } 36/\text{pb}, \text{ waiting for the update} \]

- higher mass \( m_{jj} \) as \( \mathcal{L} \) increases
- smaller region in \( \chi \) (if the detector allows)

**B**ounds on graviton exchange at tree level

\[ \chi = e^{|y_1 - y_2|} \]

arXiv:1103.3864,1102.2020
Virtual Gravitons in $\gamma\gamma$ and $\mu\bar{\mu}$ searches

$pp \rightarrow \mu\bar{\mu}$ with $\mathcal{L} \sim 1/fb$: $M_T > 2.3$ TeV

Table 3: Observed 95% upper limits on $M_\eta$ in TeV with respect to GRW and HLZ conventions for full model validity in $\sqrt{s}$ and truncation at $M_{\eta\eta} = M_\eta$ (HLZ) or $M_{\eta\eta} = \Lambda_T$ (GRW).

<table>
<thead>
<tr>
<th>$\Lambda_T$ [TeV] (GRW)</th>
<th>$M_\eta$ [TeV] (HLZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 2$</td>
<td>$n = 3$</td>
</tr>
<tr>
<td>Full</td>
<td>2.62</td>
</tr>
<tr>
<td>Truncated</td>
<td>2.56</td>
</tr>
<tr>
<td>ADD k-factor: 1.3</td>
<td></td>
</tr>
<tr>
<td>Full</td>
<td>2.70</td>
</tr>
<tr>
<td>Truncated</td>
<td>2.66</td>
</tr>
</tbody>
</table>

Figure 3: Observed 95% upper limits on $M_\eta$ for different numbers of extra dimensions $n$ with (Left) and without (Right) ADD k-factor.

$pp \rightarrow \gamma\gamma$ with $\mathcal{L} \sim 1/fb$: $M_T > 2.7$ TeV

Table 2: Table of 95% CL lower limits on $M_0$ (in TeV), as a function of the number of EDs in the HLZ convention for two different values of the ADD signal $K$ factor. All limits are computed with a signal cross section truncated to zero when $\sqrt{s} > M_0$.

<table>
<thead>
<tr>
<th>$K$ factor</th>
<th>$n_{ED} = 2$</th>
<th>$n_{ED} = 3$</th>
<th>$n_{ED} = 4$</th>
<th>$n_{ED} = 5$</th>
<th>$n_{ED} = 6$</th>
<th>$n_{ED} = 7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>3.2</td>
<td>3.4</td>
<td>2.8</td>
<td>2.6</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>1.6</td>
<td>3.5</td>
<td>3.7</td>
<td>3.1</td>
<td>2.8</td>
<td>2.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Figure 4: Signal cross section parameterization as a function of the strength of the ED effects, $\eta_C$ (left) and as a function of $1/M_0^2$ for the $n_{ED} = 2$ case (right).

EXO-11-039

EXO-11-038
\( \frac{d\sigma}{d\chi} \) angular distribution, \( \chi \equiv \exp |y_1 - y_2| \)

Being the mediator a spin-2 each vertex has a \( p_T^2 \) dependence as opposed to the \( p_T \) dependence of a spin-1.

- Signal gives more central events (small \( \chi \))

\[
\mathcal{A} = S_{\delta,\Lambda}(s) \left( T_{\mu\nu} T^{\mu\nu} - \frac{T_{\mu} T_{\nu}^*}{\delta + 2} \right)
\]

\[
S_{\delta,\Lambda}(s) = \frac{1}{M_D^{\delta+2}} \int_{|q|<\Lambda} \frac{d^\delta q}{s - q^2 + i\epsilon}
\]
$\frac{d\sigma}{d\chi}$ angular distribution, $\chi \equiv \exp |y_1 - y_2|$

ATLAS and CMS with 36/pb

$\delta = 2$ extra dimensions

$\delta = 6$ extra dimensions
\[ \frac{d\sigma}{d\chi} \] angular distribution, 
\[ \chi \equiv \exp |y_1 - y_2| \]

ATLAS and CMS with 36/pb plus monojet searches


- ED pushed in the multi-TeV region
Extending the reach of ED searches

**limits from $j+m\text{MET}$ and $\gamma+m\text{MET}$**

- Extra-dimensions searches
  - EXO-11-058, EXO-11-059, ATLAS-CONF-2011-096
  
  \[
  \text{mET from } g_n \quad n = 1, 2, \ldots
  \]

- dark matter production (see T. Tait)
  
  \[
  \text{DM} \quad \text{DM} \quad \text{jet}
  \]

**Sparse thoughts:**

*(personal set of open questions)*

- **one or many** invisible body final states?
  
  see R. Mahbubani and B. Gripaios on arXiv:1108.1800

- **continuous spectrum** of invisibles or just a single/multi body final state?

- any chance to catch difficult scenarios as degenerate (N)LSP in $j+m\text{MET}+\text{soft }\ell$s?
  
Conclusions

- No signal of large extra-dimensions so far ($M_D$ constrained in the multi-TeV region)
- Best bounds on tree-level gravitons from the angular distribution in $pp \rightarrow jj$
- Monojet searches can be recycled for DM searches and more (discussion?)
\[ S(s) = \frac{1}{M_D^{s+1}} \int_{|q|<\Lambda} \frac{d^4q}{s - q^2 + i\varepsilon} = \frac{\pi^{s/2} \Lambda^{s-2}}{\Gamma(s/2) M_D^{s+1}} F_3(s/\Lambda^2) \]

\[ F_{\delta+2}(x) = x F_{\delta}(x) - \frac{2}{\delta} \]

\[ F_1(x) = \frac{2}{\sqrt{x}} \arctanh \frac{1}{\sqrt{x}}, \quad F_2(x) = -\log \left(1 - \frac{1}{x}\right). \]

\[ M_S(\text{Hewett}) |_{\lambda=+1} = \left(\frac{2}{\pi}\right)^{1/2} M_S(\text{HLZ}) |_{n=4} \]

\[ \Lambda_T = M_S(\text{HLZ}) |_{n=4}. \]

Table 1. Lower limits at the 95\% CL on the effective Planck scale, \( M_S(\text{Hewett}) \), in TeV, from searches for direct graviton production at LEP. Limits from \( \sqrt{s} > 200 \) GeV data are shown in normal font; limits from 189 GeV data are in italics; limits from 184 GeV data are in bold script.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( e^+e^- \rightarrow \gamma G_{KK} )</th>
<th>( e^+e^- \rightarrow Z G_{KK} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( n=2 )</td>
<td>( n=3 )</td>
</tr>
<tr>
<td>ALEPH</td>
<td>1.10</td>
<td>0.86</td>
</tr>
<tr>
<td>DELPH</td>
<td>1.25</td>
<td>0.97</td>
</tr>
<tr>
<td>L3</td>
<td>1.02</td>
<td>0.81</td>
</tr>
<tr>
<td>OPAL</td>
<td>1.09</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 2. Loop-level graviton exchange: 95\% CL limits on the coefficient \( |c_\ell/4\pi|^{-1/2} \) (in TeV) of the dimension-6 operator \( \Upsilon \) of eq. (3) for positive and negative values of \( c_\ell \).