Precocious Diphoton Signals of the Little Radion at Hadron Colliders

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SM hierarchy problem: \( \frac{M_{\text{Planck}}}{M_{\text{EW}}} \sim 10^{16} \).

A possible explanation: warped 5th dimension [Randall, Sundrum 1999]

A slice of 5D anti-de Sitter space:
\[ ds^2 = e^{-k y} \eta_{\mu \nu} dx^\mu dx^\nu - dy^2 \]

\( k \) is the curvature scale.

UV brane at \( y = 0 \), IR brane at \( y = L \).

New particles
  - Kaluza-Klein excitations of 5D fields
  - A scalar, the radion (\( \phi \)) [Goldberger, Wise 2000]
With SM fields in the bulk, RS can address the flavor puzzle.
Introduction
Little Randall-Sundrum

- Suppose we think of RS as a model of flavor
- and don’t require it to solve the hierarchy problem.
- We can move the UV scale from $M_{\text{Planck}}$ to some lower scale.
- This relaxes some constraints and enhances KK signals.

[Davoudiasl, Perez, Soni 2008; Davoudiasl, Gopalakrishna, Soni 2009; Rehermann, Tweedie 2010]

- What does it do for the radion?
Model parameters
(just a few)

- $k$: curvature scale
- $L$: size of the fifth dimension
- $\Lambda_\phi = \sqrt{6}ke^{-kL} \sim \text{TeV}$
- $m_\phi \sim 100\ \text{GeV}$

In original RS, $kL \approx 35$; we will take $kL = 7$. 
Coupling of radion to gauge bosons
(massless ones)

\[
\mathcal{L}_A = -\frac{1}{4\Lambda_\phi kL} \left[ 1 + \frac{\alpha_G}{2\pi} b_G kL \right] \phi F_{\mu\nu} F^{\mu\nu}
\]

where \( b_G \) is the \( \beta \)-function coefficient of gauge group \( G \).

- This coupling is significantly enhanced in LRS \((kL = 7)\) relative to original RS \((kL \approx 35)\).
- Very promising for \( gg \to \phi \to \gamma\gamma \)
Radion branching fractions

LRS, $kL = 7$, $\Lambda_\phi = 3$ TeV

![Graph showing branching fractions for various processes as a function of $m_\phi$ in GeV.](image-url)
Radion branching fractions

LRS, $kL = 7$, $\Lambda_\phi = 3\,\text{TeV}$

- $\text{BR}(\phi \rightarrow \gamma\gamma) \sim 1\%$ for a wide range of radion masses.
- Compare to $\text{BR}(\phi \rightarrow \gamma\gamma) \lesssim 10^{-3}$ in original RS.
Radion branching fractions
original RS

[Toharia 2010]
Radion branching fractions

LRS, $kL = 7, \Lambda_\phi = 3$ TeV
Coupling of radion to $Z$ bosons
($W$s are similar)

\[
\mathcal{L}_Z = -\frac{\phi}{\Lambda_\phi} \left[ m_Z^2 \left( 1 - \frac{kL m_Z^2}{12 \Lambda_\phi^2} \right) Z_\mu Z^\mu + \frac{1}{4kL} Z_{\mu\nu} Z^{\mu\nu} \right]
\]

The plunge in $\Gamma(\phi \to ZZ)$ is due to a cancellation between these two terms, when $m_\phi \approx m_Z \sqrt{4kL + 2}$. 
Radion total width
compared to SM Higgs

This radion is really quite narrow.

<table>
<thead>
<tr>
<th>$m_{\phi,h}$</th>
<th>$\Gamma_h$</th>
<th>$\Gamma_\phi$ ($\Lambda_\phi = 3 \text{ TeV}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>3 MeV</td>
<td>0.4 MeV</td>
</tr>
<tr>
<td>600 GeV</td>
<td>120 GeV</td>
<td>0.9 GeV</td>
</tr>
</tbody>
</table>
Searching for the radion Signal
Searching for the radion
SM background

LO:

NLO:

(NNLO): (Neglect interference with signal.)

[Dicus, Willenbrock 1988; Dixon, Siu 2003]

All of these are included in DIPHOX. [Binoth, Guillet, Pilon, Werlen 2000]
Cuts at the Tevatron

- transverse momentum: $p_T \gamma > 25 \text{ GeV}$
- pseudorapidity: $|\eta| < 1.1$
- $\Delta R_{\gamma\gamma} \equiv \sqrt{(\Delta \varphi)^2 + (\Delta \eta)^2} > 0.4$
- hadronic $E_T < 10 \text{ GeV}$ within $\Delta R = 0.4$ of each photon
- invariant mass: $|m_{\gamma\gamma} - m_\phi| < 10 \text{ GeV}$
- 70% photon id efficiency
$2\sigma$ reach at the Tevatron

5 fb$^{-1}$ (solid), 10 fb$^{-1}$ (dashed)
CDF, 5.4 fb$^{-1}$

- $\sim 10$ events above background near $m_{\gamma\gamma} \approx 200$ GeV
- LRS can achieve this with $\Lambda_{\phi} \approx 1$ TeV.
2.3\sigma excess near \( m_{\gamma\gamma} \approx 450 \text{ GeV} \)

Difficult to achieve in LRS; requires \( \Lambda_\phi < 500 \text{ GeV} \).
$2\sigma$ reach at the Tevatron

5 fb$^{-1}$ (solid), 10 fb$^{-1}$ (dashed)
transverse momentum: $p_{T\gamma} > 30$ GeV

pseudorapidity: $|\eta| < 2.4$

$\Delta R_{\gamma\gamma} \equiv \sqrt{(\Delta \varphi)^2 + (\Delta \eta)^2} > 0.4$

hadronic $E_T < 10$ GeV within $\Delta R = 0.4$ of each photon

invariant mass: $|m_{\gamma\gamma} - m_\phi| < 10$ GeV

80% photon id efficiency
$2\sigma$ reach at the LHC, 7 TeV, 36 pb$^{-1}$

CMS sees no significant excess in 36 pb$^{-1}$. [arXiv:1103.4279]
Reach at the LHC, 7 TeV, 1 fb$^{-1}$

$5\sigma$ (solid), $3\sigma$ (dotted)
$5\sigma$ reach at the LHC, 14 TeV, 1 fb$^{-1}$
Summary

- LRS models provide an interesting geometric description of flavor.
- Enhanced couplings of the radion to gauge bosons lead to a much larger diphoton signal.
- Hints of this signal may show up at the Tevatron.
- The LRS radion can be detected at the LHC early run for a wide range of parameters.

And a final comment...

- It may be possible to observe other decay modes (e.g. $WW$), which would help to extract various combinations of model parameters and reveal the underlying physics.