Search for large extra dimensions at the Tevatron

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• Large extra dimensions
• Direct graviton production
  ➲ $\gamma + \text{MissingEnergy} \leftrightarrow \text{jet} + \text{MissingEnergy}$
  ➲ combination
• Virtual graviton exchange
• Outlook
Large Extra Dimensions (LED)

- Extra dimensions (ED) are predicted by string theories
- Can stabilize the Higgs mass
- Provide a dark matter candidate

- **ED should not be visible to us**
  - Compactification is a solution
  - Only gravity propagates in 4+d

- ➔ ADD paradigm

Each point would have additional dimension attached to it
Large Extra Dimensions (LED)

• ADD paradigm

• Large ED $\rightarrow$ compactified on a sub-millimeter scale $R$
  - Plank mass in (3+1)D related to the fundamental mass $M_D$ in 4+d
    - $M_{pl}^2 = 8\pi M_D^{2+2d}(M_D*R)^d$
  - $\rightarrow$ Fundamental scale $>\sim$ TeV
  - $\rightarrow$ $R \sim 0.1$mm (1 fm) for $d=2$ (6)

• KK graviton mode mass $\sim n/R$
  - Practically continuous spectrum
    - $\Delta M_{n,n+1} \sim 1/R$: mEv (MeV) $d=2$ (6)
    - $N>>1$ in HEP
  - in RS or UED $\Delta M \sim$ TeV $\rightarrow$ resonance
LED: collider signatures

- **Direct production**
  - Signatures:
    - jet+nothing (MET - missing E_T)
    - γ + nothing (MET)
      - Cleaner, but suppressed by α_{QED}/ α_{QCD}
    - Single mode: σ(n) ∝ 1/M_{pl}^2 → small
      - M_{pl} cancels out after sum over modes (n< n_{max} ~ [M_D*R]*[E_{max}/M_D]):
      - σ ∝ σ(n)*Sum ∝ 1/M_D^2*[s/M_D^2]^{d/2}

- **Virtual exchange**
  - Signatures:
    - Practically any pp(bar) → G → 2
    - No resonance, shape enhancement only
      - Angular shape analysis to improve sensitivity
    - Similarly, single mode * Sum
      - → σ ∝ s/Λ^4 : Λ - cutoff scale of order M_D
**Existing constraints**

- **Limits on** $M_D$ **from colliders (LEP/ Tevatron) are in 1TeV range**
  - $R < 0.2$ mm for $d=2$ to $R < 30$ fm for $d=6$

- **Constraints from limits on modification of Newton law**
  - Stronger than collider limits for $d=2$: $R < 37$ µm [PDG 2007], equivalent of $M_D > 3.6$ TeV

- **Stronger constraints for** $d<4$ **from astrophysics** [PDG 2007]
  - Up to $R < 10^{-10}$ m (700 TeV) for $d=2$ from neutron stars
  - Many assumptions about star internals, sensitive only to low $n/R$
    - → This limit can be relaxed while collider limits are the same

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**CDF Run II (368 pb⁻¹)**

<table>
<thead>
<tr>
<th>n</th>
<th>$M_D$ (TeV)</th>
<th>$R$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$&gt;1.18$</td>
<td>$&lt;0.35$</td>
</tr>
<tr>
<td>3</td>
<td>$&gt;0.99$</td>
<td>$&lt;3.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>4</td>
<td>$&gt;0.91$</td>
<td>$&lt;1.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>5</td>
<td>$&gt;0.86$</td>
<td>$&lt;3.5 \times 10^{-10}$</td>
</tr>
<tr>
<td>6</td>
<td>$&gt;0.83$</td>
<td>$&lt;3.4 \times 10^{-11}$</td>
</tr>
</tbody>
</table>
LED in jet + MET

• **Data sample of 1.1 fb⁻¹**
  - collected with a jet trigger with $E_T > 100$ GeV

• **Data-driven estimates of the major backgrounds.**
  - Electroweak ($\text{jet} + Z \rightarrow \nu \nu$ and $W \rightarrow l \nu$: $l$ not identified)
  - QCD (mismeasured jets) is smaller -- ~6% of total background

• **Selections:**
  - Leading jet $E_T > 150$ GeV
  - 2nd leading jet $E_T(2) < 60$ GeV to increase acceptance (ISR/FSR)
  - $\text{MET} > 120$ GeV, away (in $\phi$) from any jet
  - No isolated tracks ($P_T > 10$ GeV) to remove $W(\rightarrow \ell \nu)+\text{jets}$
LED in jet+MET: example event in data

Jet $E_T = 419$ GeV, $\text{MET} = 417$ GeV
LED in jet+MET: results

<table>
<thead>
<tr>
<th>Background</th>
<th>Expected Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to \nu\nu$</td>
<td>390 ± 30</td>
</tr>
<tr>
<td>$W \to \tau\nu$</td>
<td>187 ± 14</td>
</tr>
<tr>
<td>$W \to \mu\nu$</td>
<td>117 ± 9</td>
</tr>
<tr>
<td>$W \to e\nu$</td>
<td>58 ± 4</td>
</tr>
<tr>
<td>$Z \to ll$</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>QCD</td>
<td>23 ± 20</td>
</tr>
<tr>
<td>$\gamma$ Jet</td>
<td>17 ± 5</td>
</tr>
<tr>
<td>Non-Collision</td>
<td>10 ± 10</td>
</tr>
<tr>
<td><strong>Total Predicted</strong></td>
<td><strong>808 ± 62</strong></td>
</tr>
<tr>
<td><strong>Data Observed</strong></td>
<td><strong>809</strong></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>$n$</th>
<th>$M_D$ (TeV)</th>
<th>$R$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$&gt; 1.31$</td>
<td>$&lt; 0.279$</td>
</tr>
<tr>
<td>3</td>
<td>$&gt; 1.08$</td>
<td>$&lt; 3.15 \times 10^{-6}$</td>
</tr>
<tr>
<td>4</td>
<td>$&gt; 0.98$</td>
<td>$&lt; 1.01 \times 10^{-8}$</td>
</tr>
<tr>
<td>5</td>
<td>$&gt; 0.91$</td>
<td>$&lt; 3.20 \times 10^{-10}$</td>
</tr>
<tr>
<td>6</td>
<td>$&gt; 0.88$</td>
<td>$&lt; 3.16 \times 10^{-11}$</td>
</tr>
</tbody>
</table>
LED in γ+MET: Photon selection

- Events with high-$E_T$ photon + nothing
- Important to suppress non-collisions/fake photons

**D0**

- Photon pointing
  - Fine segmentation of EM calorimeter to separate real photons from cosmic and jet backgrounds

**CDF**

- Photon Timing
  - $\sim x20$ suppression of cosmics
    - $\sim 6\text{ns}/132\text{ns}$
    - (signal $\Delta t$)/(calorimeter input $\Delta t$)
    - Efficiency $\sim 100\%$ for photons from collisions

- Topological cuts:
  - Beam halo is negligible
    - Cosmics suppressed $\sim x30$ more
- After $\sim x600$ suppression cosmics are still 20% of the total background
LED in $\gamma + \text{MET}$: data

- Similar selections
  - photon $E_T > 90$ GeV
  - $|\eta| < 1$
  - Jet/high-$p_T$ track veto

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.0 fb$^{-1}$</td>
<td>1.0 fb$^{-1}$</td>
</tr>
<tr>
<td>MET cut</td>
<td>50 GeV</td>
<td>70 GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event Categories</th>
<th>CDF Events</th>
<th>D0 Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmics + Halo</td>
<td>$9.8 \pm 1.3$</td>
<td>$2.8 \pm 1.4$</td>
</tr>
<tr>
<td>Fake photons</td>
<td>-</td>
<td>$2.2 \pm 1.5$</td>
</tr>
<tr>
<td>$W \rightarrow l \rightarrow \gamma$</td>
<td>$3.6 \pm 0.4$</td>
<td>$3.8 \pm 0.3$</td>
</tr>
<tr>
<td>$W\gamma \rightarrow \text{lost lepton} + \gamma$</td>
<td>$5.0 \pm 1.4$</td>
<td>$1.5 \pm 0.2$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow \gamma$</td>
<td>$2.3 \pm 0.6$</td>
<td>-</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow \nu\nu\gamma$</td>
<td>$25.2 \pm 2.8$</td>
<td>$12.1 \pm 1.3$</td>
</tr>
<tr>
<td>Total</td>
<td>$46.7 \pm 3.0$</td>
<td>$22.4 \pm 2.5$</td>
</tr>
<tr>
<td>Data</td>
<td>40</td>
<td>29</td>
</tr>
</tbody>
</table>
LED: constraints from γ+MET

<table>
<thead>
<tr>
<th>d, LED</th>
<th>Observed (expected) 95% CL lower limit on $M_D$ in GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CDF preliminary 2 fb$^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>1080 (1000)</td>
</tr>
<tr>
<td>3</td>
<td>1000 (940)</td>
</tr>
<tr>
<td>4</td>
<td>970 (910)</td>
</tr>
<tr>
<td>5</td>
<td>930 (880)</td>
</tr>
<tr>
<td>6</td>
<td>900 (860)</td>
</tr>
<tr>
<td>7</td>
<td>797 (801)</td>
</tr>
<tr>
<td>8</td>
<td>778 (786)</td>
</tr>
</tbody>
</table>

• Updates with more data γMET@D0 expected soon
LED in $\gamma$+MET and jet+MET combined

- Limits from jet+MET and $\gamma$+MET combined give better sensitivity
- Similar sensitivity in jet+MET and $\gamma$+MET for $d>3$
- Tevatron combination is en course
- NB: from Newton law tests $M_D > 3.6$ TeV for $d=2$
Virtual $G$ exchange: $\rightarrow \gamma\gamma/ee/\mu\mu$

- High mass $\gamma\gamma/ee/\mu\mu$ final state
  - Look for smooth excess at high mass
- Set limits based on $(M, |\cos\theta^*|)$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma/ee$ 200 pb$^{-1}$</td>
<td>d=2, d=3, d=4, d=5, d=6, d=7</td>
<td>$\lambda=1$</td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$ 246 pb$^{-1}$</td>
<td>1.43, 1.67, 1.43, 1.29, 1.20, 1.14</td>
<td>1.28</td>
<td></td>
</tr>
</tbody>
</table>

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Searches for LED at the Tevatron
Virtual G exchange: $\to ZZ$

- $ZZ\to 4\ell$ from D0 (1 fb$^{-1}$)
  - $\to \sigma(pp\to ZZ) < 4$ pb
    - At 95% C.L.
  - arXiv:0712.0599

- $ZZ\to 4\ell/2\ell2\nu$ from CDF (2 fb$^{-1}$)
  - $\to \sigma(pp\to ZZ) = 1.4 \pm 0.7$ pb
    - $>4\sigma$ evidence
  - arXiv:0801.4806v1

- Can expect limit on $\Lambda$ in 1.5-2.5 TeV range
Outlook

- No evidence for large extra dimensions has been seen
  - Same for other kinds of ED

- Both direct production and virtual exchange of LED graviton are explored
  - Sensitivity to the fundamental mass scale is
    - $M_D \gtrsim 1 \text{ TeV}$ in direct production
    - $\Lambda \gtrsim 1.5 \text{ TeV}$ in virtual exchange

- Looking forward to more data
BACKUP SLIDES
LED

ADD Paradigm:
- Pro: "Eliminates" the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the "bulk" space
- Size of ED's (n=2-7) between ~100 µm and ~1 fm
- Black holes at the LHC and in the UHE cosmic rays
- Con: Doesn't explain why ED are so large

TeV^{-1} Scenario:
- Pro: Lowers GUT scale by changing the running of couplings
- Only gauge bosons (g/γ/W/Z) "live" in ED's
- Size of ED's ~1 TeV^{-1} or ~10^{-19} m – i.e., natural EWSB size
- Con: Gravity is not in the picture

RS Model:
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits

Greg Landsberg, Searches for New Physics with Early LHC Data
Large extra dimensions

- **Gravitational Potential in 4 Dimensions (Newton)**
  \[ V(r) = G_N \frac{m_1 m_2}{r} = \frac{1}{(M_{Pl})^2} \frac{m_1 m_2}{r} \]

- **n extra dimensions, compactified at radius R**
  \[ r \ll R \quad V(r) \sim \frac{1}{(M_D)^{n+2}} \frac{m_1 m_2}{r^{n+1}} \quad \Rightarrow \quad \quad V(r) \sim \frac{1}{(M_D)^{n+2}} \frac{m_1 m_2}{R^n} \frac{1}{r} \quad r \gg R \]

At large distances, must return to original potential

\[ (M_{PL})^2 \sim R^n (M_D)^{2+n} \]