The Search for Extra Dimensions at Present Colliders

Stefan Ask
(Lund University / DELPHI)

Studies
- Graviton Emission
- Virtual Graviton Exchange
- Branon Search
- Gauge boson KK modes
- TeV String Search
- Radion Search
- Graviton Resonances
**Outline**

**Introduction**
- The theoretical scenarios

**Graviton Emission**
- ADD Scenario
  - ALEPH DELPHI L3 Final Results
  - **ADLO Combined Results**
  - CDF D0 Results

**Graviton Exchange**
- ADD Scenario
  - ADLO Combined Results
  - CDF D0 H1 ZEUS Results

**Branon Search**
- ADD Scenario
  - L3 Results

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**Main Data Sets**

- **Gauge Boson KK modes** (ADD Scenario)
  - D0 H1 Results

- **TeV String Search** (ADD Scenario)
  - L3 Results

- **Radion Search** (ADD Scenario)
  - RS Scenario
  - OPAL Results

- **Graviton Resonances** (ADD Scenario)
  - RS Scenario
  - CDF D0 Results

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**Theoretical scenarios**

- ADD Scenario
- RS Scenario

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**All Limits Computed at 95% CL**

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**Extra Dimensions and Branes**

**Mainly Two Brane Scenarios Studied**

- The ADD Scenario
- The Randall-Sundrum scenario (RS1)

**Brane with 3 Spatial Dimensions in Bulk with D-3 Additional (Extra) Dimensions**

- Brane picture suggested by several String Models
- Gravity weak on the brane since it acts in a more extended space than the brane
- Gravity Phenomena appear at, \( M = [M_D, \Lambda_w] \sim 1 \text{ TeV} \)
  
  \[ M \ll M_p \]  
  "Solves" the hierarchy problem

- SM particles confined to the brane
- Gravity propagates in whole D-dim space
- (Non-SM Gauge bosons propagates in some extra dim)
**Gravity Phenomena in 4-dim (on the brane)**

**Compactified Extra Dimensions**

- Graviton Kaluza-Klein Modes (KK-tower)

\[ m_{KK}^2 = \sum_d p_d^2, \quad d = 4, ..., D \]

**Effective 4-dim Theory below \( M_D \)**

- Massive KK spin-2 gravitons, \( G^{(n)}_{\mu\nu} \)
- Massive KK scalar gravitons, \( H^{(n)} \)
  - Including the Radion (n=0)
- Massive scalar branons, \( \tilde{\pi} \)
  - Possible particles related to the brane dynamics

**Particles Searches**

- The ADD Scenario
  - Spin-2 graviton (Rigid brane)
  - Branons (Flexible brane)
- The Randall-Sundrum scenario (RS1)
  - Spin-2 graviton
  - Radion
The ADD Scenario (Large Extra Dimensions)  
(* N. Arkani-Hamed, S. Dimopoulos, G. Dvali)

Extra dimensions are  
• **Compactified**  
  (normally assumed on a torus and with equal radii, R)  
• **Large**  
  (R up to about 1mm)

**Bounds**  
Gravity Experiment, Cosmology and Astrophysical Constraints

- No hierarchy due to large volume of the compactified space  
  \[ M_p^2 = 8\pi R^n M_D^{n+2} \]  
  \[ M_D \sim 1 \text{ TeV} \]
- Dense KK-tower  
  \[ \Delta m_{KK} \propto 1/R \]

1-dim, Newton's law would be changed at solar system distances
2-dim, Strong bounds
> 2-dim, Relatively weak bounds

**Processes (at LEP)**

**Rigid Brane**  
\[ f \gg M_D \]

Graviton Emission:  
\[ e^+ e^- \to G + \gamma \]

Graviton Exchange:  
\[ e^+ e^- \to G^* \to ff + \gamma \gamma \]

**Flexible Brane**  
\[ f \ll M_D \]

Branon Production:  
\[ e^+ e^- \to \tilde{\pi} \tilde{\pi} + \gamma / Z \]

Graviton processes exponentially suppressed,  
\[ e^{-M_p^2 s \left( 1 - \frac{x}{2\pi} \right) f^+ (2\pi)^2} \]

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\( e^+ e^- \rightarrow G + \gamma \)

\[
\frac{d^2 \sigma}{dx \gamma d \cos(\theta \gamma)} = \left( \frac{\sqrt{s}}{M_D^{n+2}} \right)^n F(n, x, \gamma, \theta \gamma)
\]

Single photon process directly sensitive to the fundamental scale of gravity \((M_D)\) and the number of dimensions \((n)\).

\( e^+ e^- \rightarrow G^* \rightarrow \gamma \gamma \)

\[
\frac{d \sigma}{d \cos(\theta)} = F(\lambda / M_H^4)
\]

Fermion and photon pair process sensitive to cut-off mass scale \((M_H)\) and the coupling \((\lambda)\).

\( \lambda = \pm 1 \) Used in the analysis

\( e^+ e^- \rightarrow \tilde{\tau} \tilde{\tau} + \gamma / Z \)

\( \tilde{\tau} \) Photon distributions similar to Graviton emission process

\[
\frac{d^2 \sigma}{dx \gamma d \cos(\theta \gamma)} = \frac{n_b}{x s} F(M_b, x, s) G(x, \gamma, \theta \gamma)
\]

Branon process sensitive to number of branons \((n_b)\), branon mass \((M_b)\) and brane tension \((f)\).

\( n_b = 1 \) Used in the analysis

\( n = 2 \)

\( M_D = 1.5 \text{ TeV} \)
The Signals at HERA and the Tevatron (ADD)

**Graviton Emission**
(Similar to $e^+ e^- \rightarrow G + \gamma$)

$[ n , M_D ]$

**Virtual Graviton Exchange**
(Similar to $e^+ e^- \rightarrow G^* \rightarrow ff / \gamma \gamma$)

$[ \lambda , M_H \text{ cut-off} ]$

**CDF + D0:** mono-jet + missing $E_T$

**CDF + D0:** High mass $ee, \mu\mu, \gamma\gamma$

$q \bar{q} \rightarrow G^* \rightarrow ff / \gamma \gamma$
(Drell-Yan like)

**H1 + ZEUS:** High $Q^2$ DIS

$e^\pm q \rightarrow (G^*) \rightarrow e^\pm q$
(Neutral-current like)

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ADLO: Graviton + $\gamma$ Production

Results using year 2000 & 1999 data not available yet.

Low-energy photon selection barrel only

Good Agreement between Data and SM Expectation for ALEPH, DELPHI, L3 and OPAL
**ADLO: Graviton + γ Production**

No Indications of a Signal

<table>
<thead>
<tr>
<th>n</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.26</td>
<td>1.31 (1.27)</td>
<td>1.50 (1.49)</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>1.02 (0.98)</td>
<td>1.14 (1.12)</td>
</tr>
<tr>
<td>4</td>
<td>0.77</td>
<td>0.82 (0.80)</td>
<td>0.91 (0.89)</td>
</tr>
<tr>
<td>5</td>
<td>0.65</td>
<td>0.67 (0.67)</td>
<td>0.76 (0.75)</td>
</tr>
<tr>
<td>6</td>
<td>0.57</td>
<td>0.58 (0.58)</td>
<td>0.65 (0.64)</td>
</tr>
<tr>
<td>7</td>
<td>---</td>
<td>---</td>
<td>0.57 (0.56)</td>
</tr>
<tr>
<td>8</td>
<td>---</td>
<td>---</td>
<td>0.51 (0.51)</td>
</tr>
</tbody>
</table>

**Final M_D Limits (TeV) [ Obt. (Exp.) ]**

ALEPH and DELPHI show a similar sensitivity whereas that of L3 is higher.
**Combined: Graviton + γ**

Measurement of scaling factor, \( x = \frac{1}{(M_D)^{n+2}} \)

Combined Likelihood

\[
\mathcal{L}(x) = \mathcal{L}(x)^{ALEPH} \times \mathcal{L}(x)^{DELPHI} \times \mathcal{L}(x)^{L3}
\]

\[
CL = \frac{\int_0^{x_{95}} \mathcal{L}(x) \, dx}{\int_0^{\infty} \mathcal{L}(x') \, dx'} = 0.95
\]

**L3 DELPHI Preliminary**

ADL Combined Limit

<table>
<thead>
<tr>
<th>( n )</th>
<th>( 1/(M_D)^{n+2} )</th>
<th>( M_D ) (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-0.02 +/- 0.08</td>
<td>&gt; 1.60</td>
</tr>
<tr>
<td>3</td>
<td>-0.09 +/- 0.22</td>
<td>&gt; 1.20</td>
</tr>
<tr>
<td>4</td>
<td>-0.3 +/- 0.8</td>
<td>&gt; 0.94</td>
</tr>
<tr>
<td>5</td>
<td>-0.9 +/- 3.3</td>
<td>&gt; 0.77</td>
</tr>
<tr>
<td>6</td>
<td>-4.8 +/- 15.2</td>
<td>&gt; 0.66</td>
</tr>
</tbody>
</table>
CDF/D0: Graviton + Jet Production

$p \bar{p} \rightarrow Jet + E_T$

Tevatron Run I Limits

<table>
<thead>
<tr>
<th>n</th>
<th>CDF $M_D$ (TeV)</th>
<th>D0 $M_D$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&gt; 1.00</td>
<td>&gt; 0.89</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>&gt; 0.73</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 0.77</td>
<td>&gt; 0.68</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>&gt; 0.64</td>
</tr>
<tr>
<td>6</td>
<td>&gt; 0.71</td>
<td>&gt; 0.63</td>
</tr>
</tbody>
</table>

[Preliminary Run II Results]
**Combined: Graviton + γ**

- **Graviton + γ**

![Graph of Graviton + γ](image)

**ALEPH DELPHI L3**

**Preliminary**

**e\(^+\)e\(^-\) → γG**

- **LEP limits increasingly stringent with lower number of extra dimensions compared to the D0/CDF results**

(D0/CDF results are based on Run I data only)

\[
G_N^{-1} = 8\pi R^n M_D^{n+2}
\]

<table>
<thead>
<tr>
<th>(n)</th>
<th>(R (mm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&lt; 0.19</td>
</tr>
<tr>
<td>3</td>
<td>&lt; 2.6x10(^{-6})</td>
</tr>
<tr>
<td>4</td>
<td>&lt; 1.1x10(^{-8})</td>
</tr>
<tr>
<td>5</td>
<td>&lt; 4.1x10(^{-10})</td>
</tr>
<tr>
<td>6</td>
<td>&lt; 4.6x10(^{-11})</td>
</tr>
</tbody>
</table>

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**ADLO: Virtual Graviton Exchange**

Fit to LEP combination of the differential Bhabha and photon pair cross section (Fit-Parameter, $x_H = \frac{\lambda}{M_H^4}$)

Preliminary LEP Averaged $\frac{d\sigma}{d\cos\Theta}(e^+e^-)$

- $e^+ e^- \rightarrow e^+ e^-$
- $M_H > 1.20 TeV (\lambda = +1)$
- $M_H > 1.09 TeV (\lambda = -1)$

- $e^+ e^- \rightarrow \gamma \gamma$
- $M_H > 0.93 TeV (\lambda = +1)$
- $M_H > 1.01 TeV (\lambda = -1)$
**CDF/D0+H1/ZEUS** : Virtual Graviton Exchange

**CDF:** \( q\bar{q} \rightarrow G^* \rightarrow ee \)

**D0:** \( q\bar{q} \rightarrow G^* \rightarrow ee \gamma\gamma \)

**H1 / ZEUS:** \( e^\pm q \rightarrow (G^*) \rightarrow e^\pm q \)

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**Diagrams:**

- **CDF / D0:** \( M_H > 0.96 / 1.28 \)
  - **H1 / ZEUS:** \( 0.82 / 0.78 \) **TeV** (\( \lambda = +1 \))
  - \( M_H > 0.99 / 1.16 \)
  - **H1 / ZEUS:** \( 0.78 / 0.79 \) **TeV** (\( \lambda = -1 \))

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**L3: Branon Search**

\[ e^+ e^- \rightarrow \tilde{\pi} \tilde{\pi} + \gamma / Z \]

- Single photon events
  (as for the G+γ search)

- Single Z signature events
  (Unbalanced hadronic events with visible mass compatible with m_z)

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**Diagram:**

- **Data, \( \sqrt{s} = 198 \text{ GeV} \)**
- **Background**
- **SM + branon signal (f=40 \text{ GeV})**

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**Legend:**

- \( \tilde{\pi} \tilde{\pi} \gamma \): \( f > 180 \text{ GeV} \), \( M_b > 103 \text{ GeV} \)
- \( \tilde{\pi} \tilde{\pi} Z \): \( f > 47 \text{ GeV} \), \( M_b > 54 \text{ GeV} \)

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**D0+H1: Gauge Bosons in TeV⁻¹ Sized Extra Dimensions**

If gauge bosons have access to (ADD like) extra dimensions of the size, \( R = M_C^{-1} \sim \text{TeV}^{-1} \)

Gauge bosons with mass, \( M_{KK}^2 = m_0^2 + \frac{n^2}{R^2} \)

E.g. \( \gamma_{(n=0)} = \gamma_{SM} \)

\( \gamma_{(n>0)} \rightarrow m_{\gamma_{(n^\prime)}} = n' M_C \)

\( M_C \gg \sqrt{s} \) assumed

“Contact interactions” (virtual contributions)

(* K. Cheung, G. Landsberg)

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**Phenomenological study from existing data**

<table>
<thead>
<tr>
<th>( \eta ) (TeV⁻²)</th>
<th>( \eta_{95} ) (TeV⁻²)</th>
<th>( M^\text{emp} ) (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP 2:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hadronic cross section, avg. dist., ( R_{ee} )</td>
<td>(-0.33^{+0.13}_{-0.13} )</td>
<td>(0.12)</td>
</tr>
<tr>
<td>( \mu ), ( e ) cross section &amp; avg. dist.</td>
<td>(0.69^{+0.13}_{-0.13} )</td>
<td>(0.42)</td>
</tr>
<tr>
<td>ee cross section &amp; avg. dist.</td>
<td>(-0.52^{+0.20}_{-0.20} )</td>
<td>(0.16)</td>
</tr>
<tr>
<td>LEP combined</td>
<td>(-0.28^{+0.09}_{-0.09} )</td>
<td>(0.076)</td>
</tr>
<tr>
<td>HERA:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC</td>
<td>(-2.74^{+1.49}_{-1.35} )</td>
<td>(1.59)</td>
</tr>
<tr>
<td>CC</td>
<td>(-0.57^{+1.25}_{-1.31} )</td>
<td>(2.45)</td>
</tr>
<tr>
<td>HERA combined</td>
<td>(-1.21^{+2.95}_{-3.39} )</td>
<td>(1.25)</td>
</tr>
<tr>
<td>Tevatron:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>(-0.57^{+1.12}_{-1.05} )</td>
<td>(1.96)</td>
</tr>
<tr>
<td>Tevatron dijet</td>
<td>(0.46^{+0.37}_{-0.34} )</td>
<td>(1.0)</td>
</tr>
<tr>
<td>Tevatron top production</td>
<td>(-0.53^{+0.31}_{-0.33} )</td>
<td>(9.2)</td>
</tr>
<tr>
<td>Tevatron combined</td>
<td>(-0.38^{+0.32}_{-0.38} )</td>
<td>(0.65)</td>
</tr>
<tr>
<td>All combined</td>
<td>(-0.29^{+0.09}_{-0.09} )</td>
<td>(0.071)</td>
</tr>
</tbody>
</table>

**D0** \[ q \bar{q} \rightarrow ee \]

\( M_C > 1.12 \text{ TeV} \)

**H1** \[ e^+ q \rightarrow e^+ q \] (NC)

\( M_C > 1.0 \text{ TeV} \)

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**L3: TeV String Search**

String model with ADD extra dimensions
(* S. Cullen, M. Perelstein and M. Peskin ;
E.Accomando, I. Antoniadis and K. Benakli)

- Effect on Bhabha scattering of TeV scale strings

\[
\frac{d \sigma}{d \cos \theta} = \left( \frac{d \sigma}{d \cos \theta} \right)_{SM} \left| F (M_S) \right|^2
\]

\[M_S = [\text{String scale}] = (1.6 − 3.0) \times M_D\]

- This TeV string effect would typically dominate over virtual graviton exchange

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**Obtained Limit**
\[M_S > 0.55 \text{ TeV}\]
The RS Scenario (RS1)
(* L. Randall and R. Sundrum)

Non-factorizable “warped” geometry

\[ ds^2 = e^{-2kr_c\phi} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2 \]

Gravity exponentially damped by “warp-factor”

Two Branes:
- SM confined to one brane (SM-brane)
- Gravity concentrated to the other brane (Planck-brane, due to “warped” geometry)

One Extra Dimension: (between the branes)
- Gravity exponentially damped with increasing distance from the Planck brane
  - Weak gravity on SM brane
- Local fluctuations of inter-brane distance
  - The Radion, massive scalar
- Small \( r_c \) and sizable graviton coupling
  - Spin-2 Graviton Resonances

\( r_c = \) Compactification radius (VERY small)

Gravity Scale: \( \Lambda = M_P e^{-k r_c \pi} \sim TeV \)
The RS Scenario

Radion have same Quantum Numbers as the Higgs

- Higgs – Radion mixing, into one Higgs-like and one Radion-like state (h & r)

Both h and r are mainly produced at LEP in the “Higgs-strahlung” process

\[ e^+ e^- \rightarrow Z + h/r \]

Which depends on the RS parameter space

\[ \xi = \text{Mixing parameter} \]
\[ \Lambda = \text{Mass scale on SM brane} \]
\[ m_h = \text{Mass of Higgs-like state} \]
\[ m_r = \text{Mass of Radion-like state} \]

(* C. Csaki, M.L. Graesser and G.D. Kribs)

First Graviton KK mode \( G^{(n=1)} \) will be in the order of a TeV

- LEP and HERA are insensitive
- Possible graviton resonance at the Tevatron

\[ q \bar{q} \rightarrow G^* \rightarrow f f / \gamma \gamma \]

Which depends on the RS parameter space

\[ \frac{k}{M_p} = \text{Curvature parameter} \quad (0.1-0.01 \text{ allowed}) \]
\[ m_1 = \text{Mass of first graviton KK mode} \]
**OPAL: Radion Search**

\[ e^+ e^- \rightarrow Z + h \ | r \]

**Searches used:**
- **Standard Higgs search**
  \[ e^+ e^- \rightarrow Zh, h \rightarrow bb \]
- **Hadronically decaying Higgs search**
  \[ e^+ e^- \rightarrow Zh, h \rightarrow qq/\text{gg} \]
- **Decay mode independent Higgs search**
  \[ e^+ e^- \rightarrow Zh, h \rightarrow xx \]

- Excluded parameter space obtained by a parameter scan
- Point excluded if signal cross section exceeds the limit from any one of the three searches

Radion process suppressed with increasing \( \Lambda_w \) and at large negative mixing.
The search is sensitive to the $h$ signal over the whole parameter space

**Overall Higgs Limit**

$m_h > 58 \text{ GeV}$  Obtained

$m_h > 54 \text{ GeV}$  Expected

Not possible for the radion state due to suppressed couplings with increasing $\Lambda_w$ and decreased cross section at large negative mixing
**CDF/D0: Graviton Resonance**

**D0**  \( q\bar{q} \rightarrow G^* \rightarrow e\bar{e} l\gamma\gamma \)

**CDF**  \( q\bar{q} \rightarrow G^* \rightarrow e\bar{e} \mu\mu \)

**m_1 Limits (CDF / D0)**

\[
m_1 > \frac{700}{785} \text{ GeV} \quad (k/M_p = 0.1)
\]

\[
m_1 > \frac{200}{300} \text{ GeV} \quad (k/M_p = 0.01)
\]

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## Conclusion

- Several extra dimension models have been investigated at LEP, HERA and the Tevatron, but no indication of a signal has been observed

![Exclusion Limits Diagram]

### ADD

<table>
<thead>
<tr>
<th>n</th>
<th>$M_D$ (TeV)</th>
<th>$G \gamma [\text{Jet}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&gt; 1.60</td>
<td>$M_H &gt; 1.28 \text{ TeV} \ (\lambda = +1)$</td>
</tr>
<tr>
<td>3</td>
<td>&gt; 1.20</td>
<td>$M_H &gt; 1.16 \text{ TeV} \ (\lambda = -1)$</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 0.94</td>
<td>$\bar{\pi} \pi + \gamma / Z$</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 0.77</td>
<td>$f &gt; 180 \text{ GeV} \ (M_b = 0)$</td>
</tr>
<tr>
<td>6</td>
<td>&gt; 0.66 [&gt; 0.71]</td>
<td>$M_b &gt; 103 \text{ GeV} \ (f = 0)$</td>
</tr>
</tbody>
</table>

### RS

<table>
<thead>
<tr>
<th>$Z + h / r$</th>
<th>$G (n=1) - \text{Resonance}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_h &gt; 58 \text{ GeV}$</td>
<td>$m_1 &gt; 785 \text{ GeV} \ (k/lM_p=0.1)$</td>
</tr>
<tr>
<td></td>
<td>$m_1 &gt; 300 \text{ GeV} \ (k/lM_p=0.01)$</td>
</tr>
</tbody>
</table>

### TeV String

| $e^+ e^- \to e^+ e^-$ | $M_s > 0.55 \text{ TeV}$ |

### KK Modes

$q \bar{q} \to ee$

<table>
<thead>
<tr>
<th>$M_C &gt; 1.12 \text{ TeV}$</th>
<th>$(\text{LEP EW})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>($M_C &gt; 6.6 \text{ TeV}$)</td>
<td></td>
</tr>
</tbody>
</table>

- The results give many important constraints on models with extra dimensions, however much remains to be investigated at the LHC!