Extra Dimension

Searches at Accelerators

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Outline

Why search for Extra Dimensions (ED)?
   Motivation & different models: ADD, RS, TeV\(^1\)
How are ED detectable at accelerators?
   Signatures
Where are searches being performed?
   Accelerator facilities
What searches are being performed?
   Search channels
What are the results?
   Analysis descriptions
What are the future prospects?
   LHC MC studies
Extra dimensional Models

Alternatives to SUSY for solving the hierarchy problem:

\[ M_{EW} (1 \text{ TeV}) \ll M_{\text{Planck}} (10^{19} \text{ GeV})? \]

**ADD**

Arkani-Hamed, Dimopoulos, Dvali,

Phys Lett B429 (98)

Many large compactified EDs

In which G can propagate

\[ M_{\text{Pl}}^2 \sim R^n M_{\text{Pl}}(4+n)^{(2+n)} \]

Effective \( M_{\text{Pl}} \sim 1 \text{TeV} \rightarrow \) if compact space \( (R^n) \) is large

**RS**

Randall, Sundrum,

Phys Rev Lett 83 (99)

1 highly curved ED

Gravity localised in the ED

Planck \( \phi = 0 \) \( \Lambda_{\pi} = M_{\text{Pl}} e^{-kR_c \pi} \)

TeV brane \( \phi = \pi \)

\( \Lambda_{\pi} \sim \text{TeV} \)

if warp factor \( kR_c \sim 11-12 \)

\( k/M_{\text{Pl}}, k: \text{curvature scale} \)

See Extra Dimension lectures for more details on the theory & models!

**TeV^{-1}**

Dienes, Dudas, Gherghetta,

Nucl Phys B537 (99)

\( \text{TeV}^{-1} \) sized EDs

SM chiral fermions

SM Gauge Bosons

W, Z, \( \gamma, g \)

What are the experimental signatures at colliders?

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Experimental Signatures for ADD

- **Direct Graviton emission** in association with a vector-boson

  Signature: $M_{E_T} + \text{jet(s)}, M_{E_T} + V$
  $\sigma$ depends on the number of ED

- **Virtual Graviton exchange**

  Signature: deviations in $\sigma$ and asymmetries of SM processes
  e.g. $q\bar{q} \rightarrow l^+l^-, \gamma \gamma$
  Or new processes e.g. $gg \rightarrow l^+l^-$
  $\sigma$ independent of the number of ED$

New Parameters (*Hewett formalism*)

$M_s, M_D \sim M_{Pl(4+n)}$: string scale
$\lambda$: dimensionless parameter, $\pm 1$

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Experimental Signature for RS Model

Virtual Graviton exchange

Signature: an excess of events in dilepton/dijet/diboson channels

New parameters:

1\textsuperscript{st} graviton excitation mass: \( m_1 \)

\[ \Lambda_\pi = \frac{m_1 \bar{M}_{pl}}{k x_1}, \quad m_n = k x_n e^{k x_n} (J_1(x_n)=0) \]

Ratio: \( k/\bar{M}_{pl} \)

\[ \Gamma_1 = \rho m_1 x_1^2 (k/\bar{M}_{pl})^2 \]

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Davoudiasl, Hewett, Rizzo

hep-ph0006041
Experimental Signature for TeV-1 Size ED and KK Gauge Bosons

From 4-d point of view:
Mass of SM gauge bosons ($M_n$) that propagate in the ED are equivalent to towers of KK states with masses: $M_n = \sqrt{(M_0^2 + n^2/R^2)}$ where (n=1,2,...)

Potentially detectable consequences:
1) **Mixing** among the 0th (SM gauge boson) and the nth-modes (n=1,2,3..) of the W and Z bosons. (Since the entire tower of KK states have the same quantum numbers as their 0th-state gauge boson)
2) **Direct production and virtual exchanges** of the 0th-state gauge bosons, AND both direct production and virtual effects of the KK states of the W, Z, $\gamma$ and g bosons at high energies

New Parameters
$R=M_C^{-1}$: size of the compact dimension
$M_C$: corresponding compactification scale
$M_0$: mass of the SM gauge boson

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hep-ph/9811291
ED Search Facilities

Tevatron, Fermilab, USA

HERA, DESY, Hamburg

LEP, CERN, Geneva

CERN: world's largest particle physics laboratory

**Tevatron, Fermilab, USA**

Tevatron: Highest energy collider operating in the world!

- Run I $\sqrt{s} = 1.8$ TeV
- Run II $\sqrt{s} = 1.96$ TeV

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**LEP, CERN, Geneva**

- LEP I $\sqrt{s} = 91$ GeV
- LEP II $\sqrt{s} = 136-208$ GeV

**HERA, DESY, Hamburg**

- HERA, DESY, Hamburg
- World's only ep collider

- Run I $\sqrt{s} \sim 300$ GeV
- Run II $\sqrt{s} \sim 320$ GeV

LEP II, $\sqrt{s} = 1.96$ TeV

**LHC ~2007**

- LHC $\sqrt{s} = 14$ TeV

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General Particle Detection

- Both e and γ: deposit energy in the EM calorimeter (→EM object)
  - However, γ are uncharged, so leave no track in the tracking chamber
  - Whereas e^+/- leave a track
- Muons: leave a track in the tracking chamber
  - deposit minimum energy in the calorimeters
  - leave tracks in the muon chambers
Hermitic calorimeter (central & plug)/muon coverage
Precision tracking and silicon vertex detectors  ⇒ Excellent particle ID

Central Calorimeters

Muon System

|η| < 1

Plug Calorimeter

|η| < 1.5

1 <|η| < 3

Solenoid

Time-of-Flight

Silicon Tracker

|η| < 1

η=0

η=1.0

η=2.0

η=3.0
HERA: H1 & ZEUS

H1 is a finely segmented calorimeter
ZEUS has a compensating calorimeter
Both have good hermetic muon coverage
LEP Detectors

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## Summary of Searches performed

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<td>CDF, D0</td>
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<tr>
<td></td>
<td>ee</td>
<td>CDF, D0</td>
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<td></td>
<td>e$^{\pm}$·X</td>
<td>H1</td>
</tr>
<tr>
<td>Boson Exchange</td>
<td>ee</td>
<td></td>
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</tbody>
</table>

**Emission**

- **LED**
  - \( \gamma + \text{MET} \)

**Exchange**

- **LED**
  - $\gamma\gamma$
- **RS**
  - $\mu\mu$
- **TeV$^{-1}$**
  - ee+MET
## ED Searches

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![Diagram of Graviton Emission](image1.png)

![Diagram of Graviton Exchange](image2.png)
G emission: LEP $\gamma + \mathcal{M}_T$

LED Search Signature: $e^+e^- \rightarrow \gamma G$

G escapes detection: enhanced rate of $\gamma + \mathcal{M}_T$ events

\begin{align*}
\frac{d^3\sigma}{dx_{\gamma}d\cos\theta_{\gamma}} &= \frac{\alpha}{32\pi \Gamma(n/2)} \frac{\pi^{n/2}}{M_D^n} \left( \frac{\sqrt{s}}{M_D} \right)^{n+2} f(x_{\gamma}, \cos\theta_{\gamma}) \\
x_{\gamma} &: \text{ratio of } \gamma \text{ energy to beam energy} \\
\theta_{\gamma} &: \text{polar angle of } \gamma \text{ relative to beam line}
\end{align*}

- $d\sigma$ depends on $M_D$ and $n$
- $d\sigma$ increases rapidly at low $\gamma$ energies ($E_\gamma$) and angles

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G emission: LEP $\gamma + \text{MET}$

**Search Selection**

1 cluster in the EM calorimeter with
No matching charged track
$P_{t\gamma} > 0.02 \sqrt{s} - 0.04 \sqrt{s}$
No other significant detector activity

**Principal Background**

$e^+e^- \rightarrow \nu \nu \gamma$

**Other Background**

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

In low $P_{t\gamma}$ region: SM bgkd enhanced due to $e^+e^- \rightarrow e^+e^- \gamma(\gamma)$, where both e have low $\theta$ and cannot be detected

**LEP: ALEPH, DELPHI, L3**

$\sqrt{s} = 189-208$ GeV 1998-2000

$\sim 0.6$ fb$^{-1}$/experiment: 1.9 fb$^{-1}$ Total

**L3 DELPHI Preliminary**

Data
- $e^+e^- \rightarrow \nu \nu \gamma$
- Other Background
- $e^+e^- \rightarrow \gamma G$
  $M_D = 1$ TeV, $n = 2$

Good agreement with SM observed by all experiments
G emission: LEP $\gamma + \text{MET}$

Lower limits on the gravity scale ($M_D$) derived individually by each experiment as functions of number of ED (n).

Results are combined:

$$\sigma \propto \left(\frac{1}{M_D}\right)^{n+2}$$

<table>
<thead>
<tr>
<th>n</th>
<th>$M_D$ (TeV)</th>
<th>$R$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$&gt; 1.60$</td>
<td>$&lt; 0.19$</td>
</tr>
<tr>
<td>3</td>
<td>$&gt; 1.20$</td>
<td>$&lt; 2.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>4</td>
<td>$&gt; 0.94$</td>
<td>$&lt; 1.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>5</td>
<td>$&gt; 0.77$</td>
<td>$&lt; 4.1 \times 10^{-10}$</td>
</tr>
<tr>
<td>6</td>
<td>$&gt; 0.66$</td>
<td>$&lt; 4.6 \times 10^{-11}$</td>
</tr>
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ALEPH DELPHI L3

Preliminary

$e^+e^- \rightarrow \gamma G$

Excluded at 95% C.L.

LEP: best limits on direct G emission from collider experiments for n<6

For n>6 ….
G Emission: CDF: $\gamma$+ME$_T$

CDF also search for G emission: $\gamma$+ME$_T$

Search Selection  
- One $\gamma$ with $E_T > 55$ GeV and $|\eta|<1$
- ME$_T > 45$ GeV
- No jets with $E_T > 15$ GeV
- No tracks with $p_T > 5$ GeV

Main backgrounds

<table>
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<tr>
<th>Background</th>
<th>Expected</th>
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<tr>
<td>Cosmic ray muons</td>
<td>6.3 ± 2.0</td>
</tr>
<tr>
<td>$Z^0\gamma \rightarrow \nu\bar{\nu} + \gamma$</td>
<td>3.2 ± 1.0</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$ (“$\gamma$”$\nu$)</td>
<td>0.9 ± 0.1</td>
</tr>
<tr>
<td>Prompt diphotons</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>$W\gamma$ ($\nu\gamma$)</td>
<td>0.3 ± 0.1</td>
</tr>
</tbody>
</table>

Results

Expected background: 11.0 ± 2.3
Observed: 11

Cosmic Ray muons

Data in good agreement with SM

Cosmic Rays main background

Limits

<table>
<thead>
<tr>
<th>n</th>
<th>$M_D$ &gt; TeV</th>
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<tr>
<td>4</td>
<td>0.55</td>
</tr>
<tr>
<td>6</td>
<td>0.58</td>
</tr>
<tr>
<td>8</td>
<td>0.60</td>
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Limits not as restrictive as LEP
## ED Searches

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**Diagram:**

- **Emission**
  - $\gamma + \text{MET}$
  - jet(s) + $E_T$

- **Exchange**
  - ee + $\gamma \gamma$
  - $\mu\mu$
Real G Emission: jet(s) + ME_T

Better limits on G emission at the Tevatron from the jets + ME_T searches

Search Signature: pp → jet(s) + G

G escapes to detection into ED

→ Events with large ME_T

Recoil jet very energetic

σ falls as 1/M_D^{n+2} for all sub-processes

from Pythia

prediction from Giudice, Rattazi and Wells (hep-ph9811291)
Real G Emission: CDF: jet(s)+ME$_T$

**Search Selection**

84 pb$^{-1}$ Run Ib
jet $E_T^{1st} \geq 80$ GeV, $|\eta| < 1.1$ and ME$_T > 80$ GeV
a second jet is allowed if $E_T^{2nd} > 30$ GeV
no isolated tracks in event ($p_T \geq 10$ GeV)

**Main background**
Irreducible: $Z(\rightarrow \nu\nu)$+jets,
$W(\rightarrow \tau\nu)$+jets

**Results**
Expected: 274 ± 16
Observed: 284 events
Relative uncertainty on the signal acceptance 25 %

D0 have/also search for G emission (Run I & II): Monojet +ME$_T$
presently their limits are not as restrictive as CDFs

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G Emission Summary

LEP and Tevatron results are complementary

For n<6:
- LEP limits best
- \( \gamma + \text{MET} \)

LEP use \( \gamma + \text{MET} \), which is cleaner & has lower backgrounds than jet+\( \text{MET} \) (Tevatron), so the precision of their experiments wins out for lower values of \( n \)

For n>6:
- Tevatron limits best
- jet+\( \text{MET} \)

Tevatron better at large values of \( n \), because of the higher energy, which is a bigger effect at larger values of \( n \).

\[ \sigma \alpha \text{total number of possible modes in the KK tower} \ N_{KK} \]
\[ \sigma \alpha N_{KK} \alpha \sqrt{s-hat} \]

But this is true for each ED, so \( \sigma \alpha (\sqrt{s-hat})^n \)

\( \Rightarrow \) the difference in energy is a bigger effect for \( n=6 \) than \( n=2 \)

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### Diagrams
- **Emission**
  - LED, $\gamma+\text{MET}$
  - Emission, $ee\rightarrow\gamma\gamma$
- **Exchange**
  - LED, RS, $e^{\pm}\rightarrow\mu\mu$,
  - $\gamma\gamma\rightarrow\mu\mu$

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- Many different channels in which G exchange could be detected
- G exchange sensitive to several ED models
  - similarities/distinct features of their search strategies….
Search for G Exchange?

**Similarities**

**Search Signature**

Deviations in \((ee, \mu\mu, \gamma\gamma)\) cross sections \((\sigma)\) and angular distributions from SM processes caused by G exchange

---

**Dilepton Channel**

\( \bar{q}q, q\bar{q} \rightarrow l^+l^- \)

\( Zl^+_l^- / \gamma l^+_l^- \)

\( qg, gq \rightarrow l^+_l^- \)

\( KK_{l^+_l^-} \)

**Standard Model**

**Extra Dimensions**

**Diphoton Channel**

\( qg, gq \rightarrow \gamma\gamma \)

\( KK_{\gamma\gamma} \)

\( qg, gq \rightarrow \gamma\gamma \)

\( KK_{\gamma\gamma} \)

---

✓ Clean experimental signature \((ee,\mu\mu)\) even in a hadron collider

✓ Low backgrounds & \(Z^0\) peak used as a calibration point \((ee,\mu\mu)\)

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**Distinguish New Physics Models**

Resonance in RS model and broad change in \(\sigma\) in ADD model

Spin 2 graviton – used to distinguish between other new physics
CDF Search Strategy: ee, μμ, γγ

- Perform signature based searches
  - Compare data to expectation
  - 1D fits in invariant mass performed (and angular distribution studied)
- Determine spin dependent acceptance and then σ.BR
- Interpret data & set limits on many new models!
  E.g. (ee & μμ): Spin-0 : RPV sneutrinos
  Spin-1 : Z’, Technicolor ρ, ω
  Spin-2 : RS G, LED, etc..

D0 Search Strategy: ee, μμ, γγ

- Perform more ED specific searches
- Optimise for specific search:
  - ADD case: combine ee+γγ to gain in efficiency
- 3D fits in angular distribution and invariant mass performed
# ED Searches

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**Diagram:**

1. **Emission**
   - $\gamma$ + $E_T$
   - LED
   - jet(s)$+E_T$

2. **Exchange**
   - LED
   - RS
   - TeV$^{-1}$

---

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G Exchange: D0 $ee+\gamma\gamma$ ADD LED

**ADD**: many Large ED in which gravitons can propagate

Search for spin-2 broad $\sigma$ change
⇒ study invariant mass & angular distribution

Since D0 doing a ADD specific search, not searching for any new physics...
& G couples to both $\gamma\gamma$ and $ee$
D0 combine $ee+\gamma\gamma$ ⇒ diEM search

This maximises reconstruction efficiency….
**e/γ** Id/Misid-entification in Detectors

**Similarities**

- Both e and γ deposit energy in the EM calorimeter (→EM object)

**Differences**

- However, γ are uncharged, so leave no track in the tracking chamber
- Whereas e+/− leave a track

Inefficiencies arise if:

- γ ID requires no track, but γ converts (→ee)
- e ID requires a track, but loose track due to imperfect track reconstruction/crack

To maximise reconstruction efficiency: D0 combine ee+γγ ⇒ diEM search
G Exchange: D0 ee+γγ ADD LED

Search selection  200 pb^{-1}
2 two isolated EM objects, E_T>25 GeV
2 central (CC)
or 1 plug and 1 central (EC)

MC studies show adding EE degrades the sensitivity slightly, due to the
large background in this channel

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29
D0 perform a combined fit of the invariant mass and angular information
Fit combined $M_{ee\gamma\gamma}$ and $\cos\theta^*$ spectrum to extract limits

Parameterise $\sigma$ in terms of
$$\eta = \frac{\lambda}{M_s^4}$$
$$\sigma = \sigma_{SM} + \eta\sigma_{INT} + \eta^2\sigma_{KK} + \sigma_{BG}$$

- 3D templates used to set limits
- Bayesian likelihood fitting used to set 95% CL on $\eta_G$
- $\eta_G$ translated into a 95% CL mass limit on fundamental Planck Scale ($M_s$)
D0’s highest mass events

**Hints of New Physics?**

8 events with $M > 350$ GeV

- 6 form a bump around 400 GeV
  - $Z' \rightarrow ee$ resonance?
    - No: have 1 or 0 tracks AND
    - Bump twice as narrow as expected from a narrow resonance smeared with typical D0 EM calorimeter resolution

- 2 highest mass events:
  - have very low $\cos \theta^*$ (0.01, 0.03)
  - One is a $e^+e^-$ pair and the other $\gamma\gamma$

  ⇒ excellent candidates for new physics beyond the SM!

8 events with $M > 350$ GeV

- 6 form a bump around 400 GeV
  - $Z' \rightarrow ee$ resonance?
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    - Bump twice as narrow as expected from a narrow resonance smeared with typical D0 EM calorimeter resolution

- 2 highest mass events:
  - have very low $\cos \theta^*$ (0.01, 0.03)
  - One is a $e^+e^-$ pair and the other $\gamma\gamma$

  ⇒ excellent candidates for new physics beyond the SM!

Intriguing events – but consistent with the SM

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July 25-Aug 5, 2005
DØ’s highest mass event

DØ’s highest-mass DY candidate ever observed!

“Event Callas”

Mass = 475 GeV

Looking forward to results with more data from Run II (higher statistics)!

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G Exchange: CDF ee ADD LED

CDF perform a similar search
Differences: ee channel only
fit invariant mass only

Search selection 200 pb−1
2 two isolated e, E_T > 25 GeV
2 central e (CC)
or 1 central and 1 forward e (CP)

N_{exp} = 11.1 \ N_{obs} = 14 \text{ for } M_{ee}>300 \text{ GeV/c}^2
N_{exp} = 4.6 \ N_{obs} = 9 \text{ for } M_{ee}>350 \text{ GeV/c}^2

\sigma = \sigma_{SM} + \eta \sigma_{INT} + \eta^2 \sigma_{KK}

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July 25-Aug 5, 2005
**D0 μμ ADD LED**

D0 μμ search performed in a similar way to the D0 ee+γγ search

**Search Selection** 250 pb⁻¹

- $p_T^{μ1,μ2} > 15$ GeV
- Isolated tracks
- $M_{μμ} > 50$ GeV
- Cosmics removed

---

**3D fits to extract limits**

- **Data**
- **Standard Model Monte Carlo**
- **SM + ED terms (v₀=3.0 TeV⁻¹)**

---

**D0 Run II Preliminary**

- $250 \text{ pb}^{-1}$

---

$N_{\text{exp}} = 6.4$  \ $N_{\text{obs}} = 5$  \text{ for } $M_{ee} > 300$ GeV/c²

$N_{\text{exp}} = 1.3$  \ $N_{\text{obs}} = 1$  \text{ for } $M_{ee} > 450$ GeV/c²

---

No deviation in data from SM

---

Tracey Berry  
XXXIII SLAC Summer Institute  
July 25-Aug 5, 2005
Both D0 and CDF have observed no significant excess

95% CL lower limits on fundamental Planck scale ($M_s$) in TeV, using different formalisms:

<table>
<thead>
<tr>
<th>GRW</th>
<th>HLZ for $n=$</th>
<th>Hewett</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>D0 Run II: $\mu\mu$</td>
<td>1.09</td>
<td>1.00</td>
</tr>
<tr>
<td>D0 Run II: ee+$\gamma\gamma$</td>
<td>1.36</td>
<td>1.56</td>
</tr>
<tr>
<td>D0 Run I+II: ee+$\gamma\gamma$</td>
<td>1.43</td>
<td>1.61</td>
</tr>
<tr>
<td>CDF Run II: ee</td>
<td>1.11</td>
<td>1.32</td>
</tr>
</tbody>
</table>

D0 Run II $\mu\mu$ result: tightest limits on LED from a single measurement in this channel!

D0 combined ee+$\gamma\gamma$ Run I & Run II result is the most stringent limit on LED to date!

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July 25-Aug 5, 2005
## ED Searches

<table>
<thead>
<tr>
<th>Signature</th>
<th>Experiment</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Graviton Emission</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\gamma + \text{MET}_\gamma)</td>
<td>LEP, CDF</td>
<td>LED</td>
</tr>
<tr>
<td>jets+\text{MET}_\gamma</td>
<td>CDF, D0</td>
<td>LED</td>
</tr>
<tr>
<td><strong>Graviton Exchange</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ee+\gamma\gamma</td>
<td>D0</td>
<td>LED</td>
</tr>
<tr>
<td>ee</td>
<td>CDF, D0</td>
<td>LED, RS</td>
</tr>
<tr>
<td>(\mu\mu)</td>
<td>CDF, D0</td>
<td>LED, RS</td>
</tr>
<tr>
<td>(\gamma\gamma)</td>
<td>CDF</td>
<td>LED</td>
</tr>
<tr>
<td>e(^{+/-})X</td>
<td>H1</td>
<td>LED</td>
</tr>
<tr>
<td><strong>Boson Exchange</strong></td>
<td>ee</td>
<td>TeV(^{-1})</td>
</tr>
</tbody>
</table>

### Diagram:

**Emission**
- \(g, q\)\( \rightarrow \gamma\)\(+\)\(E_T\)\(\gamma\)
- jet(s)+\(E_T\)

**Exchange**
- \(g, q\)\( \rightarrow \mu\mu\)\(\gamma\gamma\)
**RS:** 1 extra compactified/warped ED in which $G$ can propagate

---

Search for spin-2 **resonance** in invariant mass spectrum

**Search Selection**

- $275 \text{ pb}^{-1}$
- 2 isolated EM objects with $E_T > 25 \text{ GeV}$
- 2 central e (CC)
- or 1 forward and 1 central e (EC)

$N_{\text{obs}} = 22786$
**Search Selection**

- 2 high Pt (\(>15\) GeV) \(\mu\)
- Minimum ionising particles
- Match a track in central tracking chamber
- Signal in the \(\mu\) drift chambers (if fiducial)

No opposite charge requirement, as determination of efficiency degrades fast at high \(p_T\)

Cosmic Rays reduced by requiring \(\mu\) arrival times at the \(\mu\) detector consistent with those from beam collisions

\[ N_{\text{obs}} = 17128 \]

Good agreement between data and expected background
G exchange: DØ RS

1D fits used to extract limits
Different search windows are used for the $ee+\gamma\gamma$ : $\mu\mu$ channels because of the different detector resolutions

---

$ee+\gamma\gamma$: EM energy determined using calorimeters

$\mu\mu$: $p_T$ measured in tracker

---

Tracey Berry
XXXIII SLAC Summer Institute
July 25-Aug 5, 2005
G exchange: DØ RS

1D fits used to extract limits
Different search windows are used for the ee+γγ : μμ channels
because of the different detector component resolutions

ee+γγ: EM energy determined using calorimeters

⇒ Symmetric windows
width 6 x detector resolution

μμ: pT measured in tracker

⇒ Asymmetric windows
only lower mass bound used
(due to long high-mass tail)
G exchange: DØ RS ee+γγ

significance of upward fluctuation at 400 GeV < 2σ

Small excess in \( \mu \) channel

Combined limits slightly less restrictive due to the overall small excess of observed events in the \( \mu\mu \) channel

<table>
<thead>
<tr>
<th>Graviton Mass</th>
<th>DiEM Channel Window</th>
<th>Background</th>
<th>Data Limit</th>
<th>Combined Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>190–210</td>
<td>51.5 ± 5.2</td>
<td>53</td>
<td>70.2</td>
</tr>
<tr>
<td>300</td>
<td>280–320</td>
<td>11.1 ± 1.1</td>
<td>12</td>
<td>28.9</td>
</tr>
<tr>
<td>400</td>
<td>380–420</td>
<td>2.40 ± 0.33</td>
<td>6</td>
<td>30.5</td>
</tr>
<tr>
<td>700</td>
<td>620–780</td>
<td>0.30 ± 0.25</td>
<td>0</td>
<td>8.2</td>
</tr>
<tr>
<td>800</td>
<td>700–900</td>
<td>0.13 ± 0.23</td>
<td>0</td>
<td>8.1</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>Graviton Mass</th>
<th>Dimuon Channel Window</th>
<th>Background</th>
<th>Data Limit</th>
<th>Combined Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>&gt; 160</td>
<td>90.1 ± 11.7</td>
<td>96</td>
<td>437</td>
</tr>
<tr>
<td>300</td>
<td>&gt; 230</td>
<td>26.2 ± 3.4</td>
<td>28</td>
<td>178</td>
</tr>
<tr>
<td>400</td>
<td>&gt; 270</td>
<td>14.7 ± 1.9</td>
<td>17</td>
<td>144</td>
</tr>
<tr>
<td>700</td>
<td>&gt; 300</td>
<td>10.2 ± 1.3</td>
<td>13</td>
<td>117</td>
</tr>
<tr>
<td>800</td>
<td>&gt; 300</td>
<td>10.2 ± 1.3</td>
<td>13</td>
<td>115</td>
</tr>
</tbody>
</table>

---

Data
Total Background
SM Background
QCD Background
300 GeV RS Graviton

DØ Run II, 275 pb⁻¹

DØ Run II, 246 pb⁻¹
G exchange: DØ RS

Excluded mass limits:
- 785 GeV for \( k/M_{Pl} = 0.1 \)
- 250 GeV for \( k/M_{Pl} = 0.01 \)

Below excluded from precision electroweak data

\( \Lambda_{\pi} > 10 \text{ TeV} \) which requires a significant amount of fine-tuning

Most restrictive limits on the RS model parameters to date!
CDF also performed a Run II RS search in the \(ee\) (\(\gamma\gamma\) separately) channel
- include CC + CP (same as ADD \(ee\) data)
- add PP \(ee\) events

Search Selection
2 forward EM clusters (PP) isolated with \(E_T > 25\) GeV

New for Run II:
increase acceptance!

New tracking algorithm developed for P photons – require a silicon track

QCD dijets (misidentified jet) background larger in the plug region than in central

\[ N_{exp} = 2.7 \pm 0.7 \quad N_{obs} = 8 \text{ for } M_{ee} > 300 \text{ GeV/c}^2 \]
\[ N_{exp} = 1.4 \pm 0.3 \quad N_{obs} = 3 \text{ for } M_{ee} > 350 \text{ GeV/c}^2 \]
Backgrounds

- Standard Model diphoton production (dominant at very high masses)
- Fakes: $\gamma$-jet and jet-jet, where jet fragments into a hard $\pi^0 \rightarrow \gamma \gamma$

Search Selection

2 isolated $\gamma$ $E_T > 15$ GeV
2 central $\gamma$ (CC)

$N_{exp} = 4.2 \pm 1.0$ $N_{obs} = 1$ for $M_{ee} > 300$ GeV/c$^2$

$N_{exp} = 1.5 \pm 0.5$ $N_{obs} = 1$ for $M_{ee} > 350$ GeV/c$^2$
G Exchange: CDF RS $\mu\mu$

**Search Selection**
- 2 isolated $\mu$, $P_T > 20$ GeV
- $|\eta_{\mu_1}| < 1$, $|\eta_{\mu_2}| < 1.5^*$
- Veto cosmic rays using track-timing cuts

- **Muon System**
  - $|\eta| < 1$
  - $|\eta| < 1.5$

- **Solenoid**
- **COT**
- **Time-of-Flight**
- **Silicon Tracker**

**CDF RUN II Preliminary (200 pb$^{-1}$)**

$N_{exp} = 5.2 \pm 0.3$, $N_{obs} = 6$ for $M_{ee} > 300$ GeV/c$^2$

$N_{exp} = 3.2 \pm 0.2$, $N_{obs} = 1$ for $M_{ee} > 350$ GeV/c$^2$

*$\mu_2$ may include tracks w/o $\mu$-chamber information

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CDF RS Graviton Limits

Setting 95 % C.L. upper limits on $\sigma \cdot \text{BR}(\sigma \rightarrow \gamma \gamma/\ell \ell)$:

- $\gamma\gamma$: Like D0 $ee+\gamma\gamma$, CDF use $\pm 3\sigma$ windows around $M_G$, but in 1D only.
- $ee+\mu\mu$: CDF use a binned likelihood method to fit 1D $M_{\ell\ell}$ spectra.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (pb$^{-1}$)</th>
<th>$M_G$ (GeV/c$^2$) K/$M_{Pl}$=0.01</th>
<th>$M_G$ (GeV/c$^2$) K/$M_{Pl}$=0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>200</td>
<td>200</td>
<td>640</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>200</td>
<td>170</td>
<td>610</td>
</tr>
<tr>
<td>$ee+\mu\mu$</td>
<td>200</td>
<td>200</td>
<td>700</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>345</td>
<td>220</td>
<td>690</td>
</tr>
</tbody>
</table>

- $ee$ has largest acceptance at low mass
- $\gamma\gamma$ has largest acceptance at high mass
- $\text{BR}(G \rightarrow \gamma\gamma) = 2 \times \text{BR}(G \rightarrow ee)$

CDF limits not as exclusive as D0’s

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CDF perform 1-D fits, but also study (ee, $\mu\mu$, $\gamma\gamma$) angular distributions.

Good agreement with SM prediction.
## ED Searches

<table>
<thead>
<tr>
<th>Signature</th>
<th>Experiment</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graviton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td>γ+MET</td>
<td>LED</td>
</tr>
<tr>
<td></td>
<td>jets+MET</td>
<td>CDF, D0</td>
</tr>
<tr>
<td>Graviton</td>
<td>ee+γγ</td>
<td>D0</td>
</tr>
<tr>
<td>Exchange</td>
<td>ee</td>
<td>CDF, D0</td>
</tr>
<tr>
<td></td>
<td>μμ</td>
<td>CDF, D0</td>
</tr>
<tr>
<td></td>
<td>γγ</td>
<td>CDF</td>
</tr>
<tr>
<td></td>
<td>e⁺⁻/X</td>
<td>H1</td>
</tr>
<tr>
<td>Boson Exchange</td>
<td>ee</td>
<td>TeV⁻¹</td>
</tr>
</tbody>
</table>

### Emission

- LED
  - γ + E_T
  - jet(s) + E_T

### Exchange

- LED
  - γγ
  - μμ
  - ee

---

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H1 LED Searches

**H1 Search Strategy**
Perform signature based searches

- Measure inclusive $\sigma$'s $e^+/e^- p \rightarrow e^+/e^- X$ over a huge range in 4-momentum transfer ($Q^2$)
- Compare data to expectation

- Interpret data & set limits on many new models!
  E.g. Contact interactions
  Leptoquarks
  R-parity violating squarks
  Search for $e$ or $q$ substructure (Form Factor Analysis)

⇒ Fix the SM and its parameters, in particular the parton distributions, using experimental data at low $Q^2$, where the theory is well established.

Then extrapolate the prediction towards $Q^2$, (where distance scales down to 1/1000 of the proton radius are probed), where deviations due to new physics are expected to be most prominent & could indicate the presence of quark substructure or new particles.
G exchange: H1 LED Search

In DIS, G-exchange may contribute to the e-q subprocess, but the new interaction also induces e-g scattering which is not present in the SM.

\[
\frac{d\sigma(e^+p \rightarrow e^+X)}{dQ^2} = \int dx \left\{ q(x) \frac{d\sigma(e^+q)}{dt} + \bar{q}(x) \frac{d\sigma(e^+\bar{q})}{dt} + g(x) \frac{d\sigma(e^+g)}{dt} \right\}
\]

**To Set Limits**

- Parameterise \( \sigma \) in terms of \( \eta = \frac{\lambda}{M_s^4} \)

\[
\frac{d\sigma(e^+q \rightarrow e^+q)}{dt} = \frac{d\sigma^{SM}}{dt} + \frac{d\sigma^G}{dt} + \frac{d\sigma^{\gamma G}}{dt} + \frac{d\sigma^{ZG}}{dt}
\]

- Fit the differential \( \sigma \) to the formula above treating \( \lambda/M_s^4 \) as a free parameter
- Extract limits on \( M_s \)

**Large Extra Dimensions**

In DIS, G-exchange may contribute to the e-q subprocess, but the new interaction also induces e-g scattering which is not present in the SM.
## ED Searches

<table>
<thead>
<tr>
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<th>Model</th>
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<tbody>
<tr>
<td>Graviton Emission</td>
<td>$\gamma + \text{MET}$</td>
<td>LEP, CDF</td>
</tr>
<tr>
<td></td>
<td>jets+MET</td>
<td>CDF, D0</td>
</tr>
<tr>
<td>Graviton Exchange</td>
<td>ee+$\gamma\gamma$</td>
<td>D0</td>
</tr>
<tr>
<td></td>
<td>ee</td>
<td>CDF, D0</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu$</td>
<td>CDF, D0</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma$</td>
<td>CDF</td>
</tr>
<tr>
<td></td>
<td>e$^+/-X$</td>
<td>H1</td>
</tr>
<tr>
<td>Boson Exchange</td>
<td>ee</td>
<td>D0</td>
</tr>
</tbody>
</table>

### Diagrams

- **Emission**
  - $\gamma$ + MET, LEP, CDF
  - Jets + MET, CDF, D0
- **Graviton Exchange**
  - ee$^+/-X$, H1
  - ee, D0
  - $\mu\mu$, CDF, D0
  - $\gamma\gamma$, CDF
- **Boson Exchange**
  - ee, D0
  - ee$^+/-X$, H1
  - $\gamma\gamma$, CDF
TeV⁻¹ ee Search

First dedicated experimental search for TeV⁻¹ ED at a collider

Search for effects of virtual exchanges of the KK states of the Z and γ

**Search Signature:** Signal has 2 distinct features:
- enhancement at large masses (like LED)
- negative interference between the 1st KK state of the Z/γ and the SM Drell-Yan in between the Z mass and M_C

**Search Selection** 200pb⁻¹

Same as LED diEM search except:
- at least 1 EM cluster has to have a matching track & no track isolation requirement

Data are in excellent agreement with Drell-Yan production, so proceed to set limits…

Tracey Berry
Extract limits on $M_C$ by fitting 2D distributions to the sum of the SM, interference, and the direct gravity templates.

Lower limit on the compactification scale of the longitudinal ED: $M_C > 1.12$ TeV at 95% C.L.

World Combined Limit $M_C > 6.8$ TeV at 95% C.L.

Better limits come from precision measurements.
Summary of Present Limits
But what of the Future...?

- Present limits are up to ~ 1TeV
- Future: More data to be analysed and to come:
  
<table>
<thead>
<tr>
<th>Delivered</th>
<th>HERA:</th>
<th>Tevatron:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyserd</td>
<td>~220pb(^{-1})</td>
<td>&gt; 1 fb(^{-1})</td>
</tr>
<tr>
<td>Goal</td>
<td>~80pb(^{-1})</td>
<td>~400 pb(^{-1})</td>
</tr>
<tr>
<td></td>
<td>&gt;700pb(^{-1}) (2007)</td>
<td>4.4-8.5 fb(^{-1}) (2009)</td>
</tr>
</tbody>
</table>

Promising observation potential, hope to discover ED if they exist!
Or extend limits: Tevatron Run IIa (2 fb\(^{-1}\)) extend limits:
  ADD: up to about \(M_S = 2\) TeV
  RS: \(m_1\) from 0.5 to 1 TeV for \(k/M_{Pl}\) 0.01 to 0.1

And after that.....?
What limits can we reach in the future?

- Next generation of detectors being built
  LHC (2007): $\sqrt{s} = 14 \text{ TeV}$
- What limits can we expect to reach?

MC studies already on their way!
LED ADD: G Direct Emission

γ+ ME_T

<table>
<thead>
<tr>
<th>M_D^{MAX} (TeV)</th>
<th>δ=2</th>
<th>δ=3</th>
<th>δ=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL 100fb⁻¹</td>
<td>4</td>
<td>7.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

ATLAS

To characterise the model need to measure M_D and δ

Measuring σ gives ambiguous results
(δ=2, M_D=5TeV very similar to δ=4, M_D=4TeV)

Disentangle δ and M_D:
Run at two different √s
e.g. 10 TeV and 14 TeV =>
need 50 fb⁻¹.

Tracey Berry
XXXIII SLAC Sum
July 25-Aug 5, 2005
LED ADD: Virtual G Exchange

<table>
<thead>
<tr>
<th>channel</th>
<th>Luminosity</th>
<th>$\delta = 2$</th>
<th>$\delta = 3$</th>
<th>$\delta = 4$</th>
<th>$\delta = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>10 fb$^{-1}$</td>
<td>$M_s^{\text{max}}$(TeV)</td>
<td>6.3</td>
<td>5.6</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S/B</td>
<td>36/18</td>
<td>36/18</td>
<td>39/25</td>
</tr>
<tr>
<td></td>
<td>100 fb$^{-1}$</td>
<td>$M_s^{\text{max}}$(TeV)</td>
<td>7.9</td>
<td>7.3</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S/B</td>
<td>50/53</td>
<td>62/96</td>
<td>55/72</td>
</tr>
<tr>
<td>$\ell\ell$</td>
<td>10 fb$^{-1}$</td>
<td>$M_s^{\text{max}}$(TeV)</td>
<td>6.6</td>
<td>5.9</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S/B</td>
<td>33/11</td>
<td>31/8</td>
<td>30/6</td>
</tr>
<tr>
<td></td>
<td>100 fb$^{-1}$</td>
<td>$M_s^{\text{max}}$(TeV)</td>
<td>7.9</td>
<td>7.5</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S/B</td>
<td>45/48</td>
<td>38/21</td>
<td>36/16</td>
</tr>
<tr>
<td>$\gamma\gamma + \ell\ell$</td>
<td>10 fb$^{-1}$</td>
<td>$M_s^{\text{max}}$(TeV)</td>
<td>7.0</td>
<td>6.3</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>100 fb$^{-1}$</td>
<td>$M_s^{\text{max}}$(TeV)</td>
<td>8.1</td>
<td>7.9</td>
<td>7.4</td>
</tr>
</tbody>
</table>

ATLAS extends reach up to $\sim$ 6/7 TeV with 10 fb$^{-1}$/100 fb$^{-1}$ (n dependent)
RS constraints

Tevatron — 110 pb\(^{-1}\) — 2 fb\(^{-1}\)

Dijet and dilepton data

<table>
<thead>
<tr>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
</tr>
<tr>
<td>(\Lambda_\pi &lt; 10\ \text{TeV})</td>
</tr>
<tr>
<td>Oblique Parameters</td>
</tr>
<tr>
<td>Allowed Region</td>
</tr>
<tr>
<td>Curvature of 5(^{\text{th}}) dimension</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>10\ fb(^{-1})</td>
</tr>
<tr>
<td>100\ fb(^{-1})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BR(G→(\gamma\gamma)) = 2*BR(G→ee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS, 100 fb(^{-1})</td>
</tr>
<tr>
<td>95% CL exclusion limits for discovery</td>
</tr>
<tr>
<td>m_6 (GeV)</td>
</tr>
<tr>
<td>c = (K/M_{Pl})</td>
</tr>
</tbody>
</table>

LHC completely covers the region of interest

(hep-ph 0006041)
Tracey Berry

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RS constraints

**Distinguish RS model** from other new physics

- Distinguish $Z'$ (spin 1) / $G$ (spin 2) from $e^+e^-$ 1st resonance by studying angular distribution

If many resonances observed: study separation: is it characteristic Bessel spacing?

- Distinguish $Z'$ / $G$ (spin 2) from $e^+e^-$ 1st resonance by studying angular distribution

**d$\sigma$/d$M$ (pb/GeV)

- LHC
- 1500 GeV $G_{KK}$ and subsequent tower states

**K/M$_{Pl}$

- 1
- 0.5
- 0.1
- 0.05
- 0.01

**M$_{ll}$ (GeV)

- 1
- 0.5
- 0.1
- 0.05
- 0.01
TeV$^{-1}$ Sized ED & KK Gauge Boson

Fermions are open strings excitations with ends stuck to our brane but gauge Bosons could also propagate in the bulk.

Search for KK excitations of Z, γ, ...

ATLAS $M_c=4$ TeV

$\gamma^{(1)}/Z^{(1)} \rightarrow e^+e^-/\mu^+\mu^-$

- 2 TeV $e$ in ATLAS: $\Delta E/E \sim 0.7$
- $\sim 20\%$ for $\mu$
- Acceptance for leptons: $|\eta| < 2.5$

Reach: Possible to detect resonance up to 5.8 TeV

In absence of peak a 95% CL of 13.5 TeV can be achieved

G. Azuelos, G. Polesello (Les Houches 2001 Workshop Proceedings)
TeV\(^{-1}\) Sized ED & KK Gauge Boson

Distinguish RS model from other new physics

Z\(^{(1)}\) or Z\(^{'}\) or RS Graviton?

Forward-backward asymmetries:

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Concluding Remarks

- No significant sign of new physics!
- Increasing number of channels being used to search for EDs
  - Many searches underway:
    - e.g. \( pp \rightarrow \tau \tau, \ \text{pp} \rightarrow \text{jet jet}, \ \text{pp} \rightarrow G \rightarrow ZZ \)
- Existing analyses being refined & improved
  - Updates imminent e.g. \( pp \rightarrow ee, \ \text{pp} \rightarrow \text{jet+MET}, \)
- Present limits are up to \( \sim 1 \text{TeV} \)
- LHC will enable searches probe up to \( \sim 5-6 \text{ TeV} \)

Will HERA/Tevatron discover new physics before LHC?