Search for Extra Dimensions and Heavy Resonances in lepton, photon, and MET final states with the DØ Detector

Alexey Ferapontov
Brown University
for the DØ Collaboration

SUSY09, June 5th – 10th,
Northeastern University, Boston, MA
Outline

- Motivation
- The experimental apparatus
- Analyses
  - Large Extra Dimensions – photon + MET with 2.7 fb\(^{-1}\), di-electron with 1 fb\(^{-1}\)
  - Randall-Sundrum Gravitons – di-electron with 3.6 fb\(^{-1}\)
  - Z' – di-electron with 3.6 fb\(^{-1}\)
  - W' – electron + MET with 1.1 fb\(^{-1}\)
- Conclusion and prospects
The standard model
- describes interactions between three generations of quarks and leptons
- vector gauge bosons – force carriers:
  - electroweak: photon, $W^\pm$, $Z$
  - strong: gluons
- works great at low and moderate energies

Questions ...
- gravity: graviton?? - not included into the SM!
- why three generations? what is the origin of mass?
- what is the origin of dark matter?
- hierarchy problem?
- are there more than 4 space-time dimensions? etc...

Need new physics extensions to solve the problems
Large Extra Dimensions

- Planck scale $M_{pl} \sim G^{-1/2} \approx 2 \times 10^{19} \text{ GeV} \gg \text{Electroweak scale} \sim 10^3 \text{ GeV}$

- **Gravity is very weak in our 3 + 1 dimension world**
  - solution: 3 + 1 + $n$ dimensions ($n$ – extra dimensions)
  - $M_{pl}^2 = 8\pi M_D^{n+2} R^n$, where $M_D$ – fundamental Planck scale in extra dimensions, $R$ – size of extra dimensions, $M_D$ can be $O(1 \text{ TeV})$
  - graviton appears as Kaluza-Klein excitations in large extra dimensions, LED ( $R \gg$ Planck length of $10^{-33} \text{ cm}$)
  - two models: real graviton emission and virtual graviton exchange

$n = 1 \Rightarrow R \sim 10^{13} \text{ cm}$

$n = 2 \Rightarrow R \sim 1 \text{ mm}$

$n = 3 \Rightarrow R \sim 1 \text{ nm} \ldots$

$n = 7 \Rightarrow R \sim 1 \text{ fm}$
**Randall-Sundrum Gravitons**

- **Same idea: KK excitations in only 1 extra dimension**
  - parameters: $M_1$ – mass of the 1\textsuperscript{st} excited mode (lightest), and $k(8\pi)/M_{\text{pl}}$ – dimensionless coupling to the SM field
  - expect: $0.01 < k(8\pi)/M_{\text{pl}} < 0.1$

- **Curved metric with 2 branes**
  - Planck brane – gravity origin
  - SM brane – gravity is weak (exponential suppression)
  - expect $M_1 \sim O(1\ TeV)$ for large $R$

- **Spin = 2**
  - $\text{BR}(G_{\text{KK}} \rightarrow \gamma\gamma) = 2 \times \text{BR}(G_{\text{KK}} \rightarrow ee)$
Extensions of SM might require additional gauge bosons

- $W'$, $Z'$
- couple to fermions and SM gauge bosons
- search for a generic charged or neutral heavy boson

Parameters of the theory

- width, mass
- assumptions: no mixing between SM and additional gauge bosons, SM CKM matrix and couplings to fermions

Width scales with mass

\[ \Gamma_{W'} = k \frac{m_{W'}}{m_W} \Gamma_W \quad \Gamma_{Z'} = \frac{m_{Z'}}{m_Z} \Gamma_Z \]

- $k = 1$ for $M_{w'} < 180$ GeV and $k = 4/3$ for $M_{w'} > 180$ GeV
Thanks to the Beam Division!

6 fb$^{-1}$
Event selection – photon sample
- triggered by single electron triggers
- photon with $E_T > 90$ GeV, $|\eta| < 1.1$, isolated in both tracker and calorimeter; MET > 70 GeV
- clean event – no muons, jets, energetic tracks, and electromagnetic objects

Monte Carlo
- Pythia for $n = 2 – 8$

\[ q \Gamma_{KK} \]
Backgrounds

- $Z\gamma \to \nu\nu\gamma$, $W+\gamma$ – from Monte Carlo
- $W \to e\nu$, $W/Z+\text{jet}$, non-collision – from data using DCA (distance of closest approach) templates

DCA templates

- fine segmentation – pointing algorithm!
- fit sum of DCA templates to data

### Backgrounds:

<table>
<thead>
<tr>
<th></th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + \gamma$</td>
<td>$29.5 \pm 2.5$</td>
</tr>
<tr>
<td>$W \to e\nu$</td>
<td>$8.5 \pm 1.7$</td>
</tr>
<tr>
<td>Non-collision</td>
<td>$6.6 \pm 2.2$</td>
</tr>
<tr>
<td>Misidentified jets</td>
<td>$3.1 \pm 1.5$</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>$2.2 \pm 0.3$</td>
</tr>
<tr>
<td>Total background</td>
<td>$49.9 \pm 4.1$</td>
</tr>
<tr>
<td>Candidates</td>
<td>51</td>
</tr>
</tbody>
</table>

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Alexey Ferapontov

June 6th, SUSY09
• Good agreement between data and SM – proceed with limits
  • limit setting routine that compares photon $E_T$ distribution in data and signal + backgrounds for discrepancies

<table>
<thead>
<tr>
<th>$n$</th>
<th>Observed (expected) cross section limit, fb</th>
<th>Observed (expected) M(D) limit, GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>19.0 (14.6)</td>
<td>970 (1037)</td>
</tr>
<tr>
<td>3</td>
<td>20.1 (14.7)</td>
<td>899 (957)</td>
</tr>
<tr>
<td>4</td>
<td>20.1 (14.9)</td>
<td>867 (916)</td>
</tr>
<tr>
<td>5</td>
<td>19.9 (15.0)</td>
<td>848 (883)</td>
</tr>
<tr>
<td>6</td>
<td>18.2 (15.2)</td>
<td>831 (850)</td>
</tr>
<tr>
<td>7</td>
<td>15.9 (14.9)</td>
<td>834 (841)</td>
</tr>
<tr>
<td>8</td>
<td>17.3 (15.0)</td>
<td>804 (816)</td>
</tr>
</tbody>
</table>
**Event selection**
- do not distinguish between electrons and photons
- single and diEM triggers, 1.05 fb\(^{-1}\)
- 2 isolated (both tracker and calorimeter) EM objects with \(E_T > 25\) GeV, shower shape consistent with that of an EM object

**Backgrounds**
- SM Z/Drell-Yan and direct \(\gamma\gamma\) – from Pythia MC
- multijet (MJ) background – from data
  - invert shower shape criteria to estimate the shape of jets that mimic electrons/photons
  - \(h_{data} = f_{QCD} \cdot h_{MJ} + (1 - f_{QCD}) \cdot h_{SM}\)
Data Sample, 1/fb  1.05

<table>
<thead>
<tr>
<th>Candidates</th>
<th>CCCC</th>
<th>CCEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidates</td>
<td>48971</td>
<td>41978</td>
</tr>
<tr>
<td>Total background</td>
<td>48643 ± 202 ± 3732</td>
<td>42380 ± 177 ± 4488</td>
</tr>
</tbody>
</table>

- Data agree with theoretical expectations
  - compare diEM mass and \(|\cos\theta^*|\) distributions in data and signal + backgrounds
  - set 95% C.L. limits

<table>
<thead>
<tr>
<th>n</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed limit M(s), TeV</td>
<td>2.09</td>
<td>1.94</td>
<td>1.62</td>
<td>1.46</td>
<td>1.36</td>
<td>1.29</td>
</tr>
<tr>
<td>Expected limit M(s), TeV</td>
<td>2.16</td>
<td>2.01</td>
<td>1.66</td>
<td>1.49</td>
<td>1.38</td>
<td>1.31</td>
</tr>
</tbody>
</table>

PRL 102, 051601 (2009)
• **Event selection**
  - di-electron triggers, 3.6 fb\(^{-1}\)
  - 2 isolated (both tracker and calorimeter) electrons with \(E_T > 25\) GeV, shower shape consistent with electrons, spatially matched to tracks, di-electron mass > 50 GeV/c\(^2\)

• **Backgrounds**
  - Drell-Yan: \(Z/\gamma^* \rightarrow ee\); “Other SM”: \(Z/\gamma^* \rightarrow \tau\tau\), \(W+X \rightarrow ev +X\), \(WW \rightarrow eevv\), \(WZ\) where \(Z \rightarrow ee\), \(ttbar \rightarrow 2e2vbbar\) – from Pythia MC
  - multijet background – from data
    - same method as in LED diEM analysis
    - invert shower shape requirements
    - fit \(M_{ee}\) in data with a linear sum of the backgrounds
Di-electron mass spectra

- background fit region: $70 \text{ GeV/c}^2 < M_{ee} < 150 \text{ GeV/c}^2$

Using 3.6 fb$^{-1}$ of data

- good agreement between observations and SM expectations
- proceed with limits setting
Set limits on $\sigma \times \text{BR}(X \rightarrow ee)$ and mass of the resonance

- $X = \text{resonance with spin } 1 \ (Z')$, and $2 \ (G_{RS})$ with $M \geq 400 \ \text{GeV}/c^2$
- use di-electron invariant mass spectrum for limits setting

<table>
<thead>
<tr>
<th>Model</th>
<th>Expected Lower Mass Limit (GeV)</th>
<th>Observed Lower Mass Limit (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'$ (SSM)</td>
<td>949</td>
<td>950</td>
</tr>
<tr>
<td>$Z'$ ($\eta$)</td>
<td>918</td>
<td>925</td>
</tr>
<tr>
<td>$Z'$ ($\chi$)</td>
<td>834</td>
<td>800</td>
</tr>
<tr>
<td>$Z'$ ($\psi$)</td>
<td>817</td>
<td>763</td>
</tr>
<tr>
<td>$Z'$ (sq)</td>
<td>774</td>
<td>719</td>
</tr>
<tr>
<td>$Z'$ (N)</td>
<td>803</td>
<td>744</td>
</tr>
<tr>
<td>$Z'$ (I)</td>
<td>732</td>
<td>692</td>
</tr>
<tr>
<td>RS ($k(8\pi)/M_{pl} = 0.1$)</td>
<td>826</td>
<td>786</td>
</tr>
<tr>
<td>RS ($k(8\pi)/M_{pl} = 0.07$)</td>
<td>767</td>
<td>708</td>
</tr>
</tbody>
</table>

**Preliminary results**

**Di-electron + diphoton analysis with 1 fb$^{-1}$**

- limit on $M_1 = 900 \ (300) \ \text{GeV}$ for $k(8\pi)/M_{pl} = 0.1(0.01)$

**PRL 100, 091802 (2008)**
Event selection
- single EM triggers, 1 isolated central EM candidate with $E_T > 30$ GeV, shower shape consistent with that of an electron, spatial track match, MET > 30 GeV

Backgrounds
- major: $W \rightarrow e \nu$; minor: $WW$, $ZZ$, $WZ$, $Z$ – all from Pythia
- multijet (jet faking an electron) – from data:
  - sample of fakes
  - fit $M_T$ spectrum in data with sum of backgrounds

1 fb$^{-1}$: observe 452,984 candidates and $(454 \pm 35) \times 10^3$ bkg
No evidence of $W'$ in data – proceed with limits

- use $M_T$ distribution above 140 GeV to compare data and signal + backgrounds

<table>
<thead>
<tr>
<th>Backgrounds:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$875 \pm 20\text{(stat)} \pm 90\text{(syst)}$</td>
</tr>
<tr>
<td>Misidentified jets</td>
<td>$27 \pm 2\text{(stat)} \pm 2\text{(syst)}$</td>
</tr>
<tr>
<td>Other</td>
<td>$57 \pm 3\text{(stat)} \pm 4\text{(syst)}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$959 \pm 21\text{(stat)} \pm 90\text{(syst)}$</td>
</tr>
<tr>
<td>Candidates</td>
<td>967</td>
</tr>
</tbody>
</table>

95% CL limits

- upper limits on the production cross section $\times$ BR are $10 - 40$ fb for $M_{W'} = 500 - 1200$ GeV
- lower limit on $W'$ mass of 1.0 TeV

PRL 100, 31804 (2008)
Conclusion and Prospects

- DØ Collaboration has searched for new physics in the lepton, photon, and MET final states
  - no evidence for new physics found in datasets up to 3.6 fb⁻¹
  - set limits on fundamental Planck scale in LED, and masses of RS graviton and heavy resonances

- 6 fb⁻¹ already written to disks and expect up to 10 fb⁻¹ delivered (per experiment) by end of 2010
  - DØ detector is well understood
  - the datasets are much larger than those used in the analyses – already on disks
  - enough data to find new physics?
BACKUP SLIDES
DØ Detector

Photons, Central electrons (|\eta|<1.1)

Forward electrons (1.5<|\eta|<2.5)

End Calorimeter

Central Calorimeter

Muon Scintillators
Muon Chambers
Calorimeter
Toroid
Shielding

Alexey Ferapontov
June 6\textsuperscript{th}, SUSY09