Search for gravitons using merged jets from Z boson decays with the ATLAS experiment

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Outlines

Gravitons and Warped Extra Dimensions

Experimental Apparatus

Background Monte Carlo Samples

Object and Event Selection

Background Estimation

Signal Region Data

Statistical Analysis

Results
Warped Extra Dimensions

A prominent way of addressing the hierarchy problem of the Standard Model involves five-dimensional spacetime, warped by the metric:

$$ds^2 = e^{-2ky} \eta_{\mu \nu} dx^\mu dx^\nu - dy^2$$

where $0 \leq y \leq R\pi$ is the extra dimension, and $k^{-1}$ is its curvature.

In the RS1 model (the original Randall-Sundrum model):

- the graviton is concentrated here
- the entire SM is localized here where gravity is weak

Massive excited graviton modes ($G^*$) are a defining feature.
In the **bulk RS model**:

SM particles propagate in the 5D bulk...

...which can explain the wide spectrum of fermion masses

This results in heavy suppression of:

- \(qq \rightarrow G^*\) production and
- easily detectable \(G^* \rightarrow \ell\ell\) or \(\gamma\gamma\) decays

Decays to pairs of heavy particles, \(t\bar{t}, WW, ZZ\) and perhaps Higgs bosons are preferred

This analysis searches for \(G^* \rightarrow ZZ\)
$G^* \rightarrow ZZ \rightarrow \ell\ell qq$ Final State

In this search, one $Z$ decays leptonically and a $W$ or a $Z$ decays hadronically this features:

- larger branching ratio (BR) than fully leptonic decays
- fully reconstructed graviton
- much lower background than all-hadronic decays

Previous diboson resonance searches at the Tevatron

<table>
<thead>
<tr>
<th>experiment</th>
<th>$\mathcal{L}_{\text{int}}$ [fb$^{-1}$]</th>
<th>process</th>
<th>mass exclusion [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>5.4</td>
<td>$G^* \rightarrow WW$</td>
<td>300 – 754</td>
</tr>
<tr>
<td>D0</td>
<td>5.4</td>
<td>$W' \rightarrow WZ$</td>
<td>180 – 690</td>
</tr>
<tr>
<td>CDF</td>
<td>2.9</td>
<td>$G^* \rightarrow ZZ$</td>
<td>300 – 491</td>
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The Large Hadron Collider

LHC delivered more than 5 fb\(^{-1}\) of 7 TeV data to ATLAS in 2011

This analysis uses 2 fb\(^{-1}\) of data (Apr – Aug 2011)

The LHC has already delivered almost 1 fb\(^{-1}\) at 8 TeV in 2012!
...with 20 reconstructed vertices! – ‘pile-up’
Candidate graviton event

Two electrons \( m(\gamma\gamma) = 89 \text{ GeV} \)

jet

jet

good electron

electron-like jet
Electron identification

cut values depend on $\eta$ and $p_T$

**Loose cuts:**
- Hadronic leakage $\rightarrow$
- Ratio in $\eta$ of cell energies in $3 \times 7$ versus $7 \times 7$ cells
- Lateral width of the shower

**Medium cuts:**
- Loose cuts
- shower width in the first layer
- difference between the largest two energy deposits / their sum $\rightarrow$
- Track quality
- Track matching

'background electrons' from photon
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Background Monte Carlo Samples

Z+jets production represents around 90% of the background

Production of top quarks, dibosons, $W$+jets and multijets is also estimated

Monte Carlo

Several MC generators are used to simulate physics processes

- Z+jets: **ALPGEN**
- RS1 model: **PYTHIA**
- **SHERPA**
- bulk RS model: **CALCHEP**

MC events are passed through a full detector simulation and reconstructed with the same software as data

Correction factors are applied to MC events, accounting for pile-up, trigger and reconstruction efficiencies

MC events are scaled by:

- the luminosity and
- the cross section of the process...
Cross section measurements at ATLAS

Cross sections of Standard Model electroweak processes have been measured at ATLAS, in excellent agreement with predictions.

\[ \text{Data 2010} \quad \text{Data 2011} \quad \text{Theory} \]

ATLAS Preliminary
\[ \int L \, dt = 0.035 - 4.7 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]

- Theory
- Data 2010
- Data 2011

- W
- Z
- t\bar{t}
- t
- WW
- WZ
- ZZ

\[ \sigma_{\text{total}} \quad \text{[pb]} \]

- $35 \, \text{pb}^{-1}$
- $35 \, \text{pb}^{-1}$
- $1.0 \, \text{fb}^{-1}$
- $0.7 \, \text{fb}^{-1}$
- $4.7 \, \text{fb}^{-1}$
- $1.0 \, \text{fb}^{-1}$
- $4.7 \, \text{fb}^{-1}$
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Electrons and Muons  \( Z \rightarrow \ell\ell \) Preselection

Electrons are selected based on shower shape and cluster/track matching and rejected in poorly understood regions of the calorimeter.

Muons are selected based on track quality.

\( p_T > 20 \text{ GeV} \) (both electrons and muons)

An isolation requirement is used to reject leptons within jets.

- two electrons or two oppositely-charged muons
- dilepton mass consistent with \( Z \) boson \(|m_{\ell\ell} - 91 \text{ GeV}| < 25 \text{ GeV}\)
- no other electrons or muons
Jets are reconstructed using the anti-$k_t$ algorithm with cone size 0.4. Jet energies are calibrated to the hadronic scale. Standard quality criteria based on the time and pulse shape of energy deposits are applied:

$$p_T > 25 \text{ GeV}, \quad |\eta| < 2.8$$

Jet vertex fraction JVF - the energy fraction associated with the leading primary vertex - is used to reject pile-up jets:

$$|\text{JVF}| > 0.75$$
Jet Merging

As the transverse momentum of hadronic $W$ and $Z$ bosons increases, the decay products will become increasingly collimated

$$p_T(W/Z) \sim 0 \quad p_T(W/Z) \sim m(W/Z) \quad p_T(W/Z) \gg m(W/Z)$$

The quark separation $\Delta R \sim \frac{2m}{p_T}$

$$\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2}$$

With a jet cone size of 0.4, ‘jet merging’ becomes significant when $W/Z \ p_T \gtrsim 400 \text{ GeV}$
The jet mass resolution is around 8 GeV for signal mass \( \sim 1 – 1.5 \text{ TeV} \) \( \Rightarrow \) W and Z are difficult to distinguish
Jet Mass Scale Uncertainty

It is important to validate the jet mass measurement.

Track-jets are used since they are independent...

but around half of jet energy comes from neutral particles which leave no track!

So the ‘double ratio’ is used:

\[
\left( \frac{m_{\text{jet}}}{m_{\text{track-jet}}} \right)_{\text{data}} \approx \left( \frac{m_{\text{jet}}}{m_{\text{track-jet}}} \right)_{\text{MC}}
\]

The largest deviation from one is taken as JMS uncertainty: \( \sim 10\% \)

method follows studies with larger jets...
### Event Selection

<table>
<thead>
<tr>
<th>Signal region</th>
<th>Conditions</th>
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<tbody>
<tr>
<td><strong>Resolved jets</strong></td>
<td>(65 &lt; m_{jj} &lt; 115 \text{ GeV,}) (p_T^{jj} &gt; 50 \text{ GeV,}) (m_{G^*} &lt; 500 \text{ GeV})</td>
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<td><strong>(Low Mass signal)</strong></td>
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</tr>
<tr>
<td><strong>(High Mass signal)</strong></td>
<td>(p_T^{\ell\ell} &gt; 200 \text{ GeV,}) veto events in <strong>Merged jet</strong> region.</td>
</tr>
<tr>
<td><strong>Merged jet</strong></td>
<td>(m_j &gt; 65 \text{ GeV,}) (p_T^j &gt; 200 \text{ GeV,}) (p_T^{\ell\ell} &gt; 200 \text{ GeV.})</td>
</tr>
</tbody>
</table>
Resolved Jets (Low Mass signal) Region

$m_{G^*} < 500 \text{ GeV}$

no data on plots
Resolved Jets (High Mass signal) Region

\[ m_{G^*} \geq 500 \text{ GeV} \]
Merged Jet Region

$m_{G^*} \geq 750$ GeV

Events / 20 GeV

Events / 5 GeV

Events / 200 GeV

$Z/\gamma^*+\text{jets (ALPGEN)}$

$Z/\gamma^*+\text{jets (SHERPA)}$

top

diboson

$W+\text{jets}$

QCD

$G^*(1000 \text{ GeV}) \rightarrow ZZ$
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# Z+jets background normalization

For the dominant Z+jets background, both SHERPA and ALPGEN generators are used.

The difference between the two is used to estimate systematic uncertainty.

In the signal regions, data/MC disagreement can be as much as 30%.

Z+jets MC (both ALPGEN and SHERPA) is scaled to data in control regions - 'sidebands' in the dijet mass - scale factors:

\[ m_{jj} \text{ distribution (Electron channel)} \]

- **eejj**
  - **ALPGEN**: \(0.84 \pm 0.08\)
  - **SHERPA**: \(1.34 \pm 0.12\)
Other Backgrounds

Top background is checked using the $E_T^{\text{miss}}$ distribution in Low Mass Region

Multijet background is estimated using a fake-dominated sample of data

Diboson and $W+jets$ backgrounds are estimated using MC scaled by the cross section ($\sigma$)
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Resolved Jets Signal Regions

Low Mass signal region

High Mass signal region

Events / 100 GeV

Data 2.0 fb⁻¹
Z/γ+jets (ALPGEN)
Z/γ+jets (SHERPA)
other backgrounds
G*(350 GeV)→ZZ

Events / 100 GeV

Data 2.0 fb⁻¹
Z/γ+jets (ALPGEN)
Z/γ+jets (SHERPA)
other backgrounds
G*(750 GeV)→ZZ
G*(1000 GeV)→ZZ
G*(1250 GeV)→ZZ
Merged jet Signal Region

Events / 200 GeV

- Data 2.0 fb⁻¹
- Z/γ+jets (ALPGEN)
- Z/γ+jets (SHERPA)
- other backgrounds
- G*(1000 GeV)→ZZ
- G*(1250 GeV)→ZZ
- G*(1500 GeV)→ZZ

m_{llj} [GeV]
Systematic Uncertainties

Systematic uncertainties on the $Z$+jets background derived from:

• 100% systematic uncertainty on the scaling of ALPGEN
• ALPGEN − SHERPA shape difference
• MC statistics
• Heavy flavor

Largest systematics in the **Resolved jets High mass region** are:

• difference between ALPGEN and SHERPA: ±34%
• ALPGEN scale factor: 15 – 30%
• Jet energy scale uncertainty: $^{+12\%}_{-11\%}$
• MC statistics: ±5%

Largest systematics in the **Merged jet region** are:

• difference between ALPGEN and SHERPA: ±80%
• Jet mass scale uncertainty: $^{+80\%}_{-28\%}$
• Jet energy scale uncertainty: $^{+14\%}_{-15\%}$
• MC statistics: ±12%
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The CL$_s$ Method

Events are counted in windows around each signal peak

Data is compared to background-only and signal+background pseudo-experiments (PEs) including statistical and systematic uncertainties.

Confidence levels (CL) are fractions of PEs to the right of the solid line

\[
\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b} = \frac{0.04}{0.79} < 1 - 0.95 \Rightarrow \text{excluded at 95\% CL}
\]

For each mass point a value of $\sigma \times \text{BR}$ is excluded
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Limits on $\sigma \times \text{BR}$ in the RS1 model

Merged jets channel reduces limits on $\sigma \times \text{BR}$ by up to a factor of five!

Observed (expected) limits on the mass of the KK graviton are extended to 870 (950) GeV
Also...
First ever limits are set on the KK graviton in the **bulk RS model**: Observed (expected) limits on the mass are 630 (590) GeV

**Merged jets** can provide a large gain in sensitivity to high mass signals

They will become an essential part of many new physics searches, with the full 2011 data set (∼5 fb\(^{-1}\)) and 8 TeV collisions in 2012

Part of this analysis has been submitted to Physics Letters B

Just one of many limits set on extra dimensions and other new physics models at ATLAS...
ATLAS Exotics Searches* - 95% CL Lower Limits (Status: March 2012)

**Mass scale [TeV]**

- **10**
- **10**
- **10**
- **10**
- **10**

**Extra dimensions**

- Large ED (ADD) : monojet
- Large ED (ADD) : di-photon
- UED : \(E_T\) miss

**RS with \(k/M_{Pl} = 0.1\)**

- 1st generation: \(Q, Q' \rightarrow W q W q\)
- 2nd generation: \(u, u' \rightarrow W b W b\)
- 3rd generation: \(d, d' \rightarrow W t W t\)

**Large ED (ADD) : di-photon**

- \(M_{TH}/M_D = 3\): multijet, \(\Sigma p_T, N_jets\)
- ADD BH (\(M_{TH}/M_D = 3\)): SS dimuon, \(N_{ch. part.}\)
- ADD BH (\(M_{TH}/M_D = 3\)): lepton + jets, \(\Sigma p_T\)
- Quantum black hole: dijet, \(F(m_j)\)

**CI - Contact interaction**

- \(qq\ll\) CI: \(e\mu, \mu\mu, \text{combined}, m_{ll}\)
- \(u\ll\) CI: \(SS\) di-lepton + jets + \(E_T\) miss

**Scalar LQ pairs (\(\beta = 1\))**

- 1st generation: \(Q, Q' \rightarrow W q W q\)
- 2nd generation: \(u, u' \rightarrow W b W b\)
- 3rd generation: \(d, d' \rightarrow W t W t\)

**Excited fermions**

- \(T^\pm\rightarrow A^- A^\pm + 1\)-lep + jets + \(E_T\) miss
- Excited quark: dijet resonance, \(m_{ll}\)
- Excited quark: dijet resonance, \(m_{ll}\)
- Excited electron: e- \(\gamma\) resonance, \(m_{ee}\)
- Excited muon: \(\mu-\gamma\) resonance, \(m_{\mu\mu}\)

**Techni-hadrons**

- Techni-hadrons: WZ resonance (vIII), \(m_{T,WZ}\)
- Major neutr. (LRSM, no mixing): 2-lep + jets
- W_R (LRSM, no mixing): 2-lep + jets

**Other**

- H_L^± (DY prod., BR(H_L^± \rightarrow \mu\mu) = 1): SS dimuon, \(m_{\mu\mu}\)
- Color octet scalar: dijet resonance, \(m_{ll}\)
- Vector-like quark: CC, \(m_{hQ}\)
- Vector-like quark: NC, \(m_{hQ}\)

**Summary**

- **ATLAS Exotics Searches**: 95% CL Lower Limits (Status: March 2012)
- **Mass scale [TeV]**: Various limits on new states or phenomena shown
- **ATLAS Preliminary**
- **\(\int Ldt = (0.04 - 5.0) fb^{-1}\)**
- \(\sqrt{s} = 7\) TeV

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*Only a selection of the available mass limits on new states or phenomena shown*
Backup Slides
Acceptance for RS1 graviton

Jet merging becomes significant for \( m_{G^*} \gtrsim 1 \text{ TeV} \)
Z boson decaying to muons

Z-→μμ candidate in 7 TeV collisions

Run Number: 154822, Event Number: 14321500
Z: M\text{inv}=87 \text{ GeV}, \text{Pt}=26 \text{ GeV}
\text{Pt}(\mu^+) = 45 \text{ GeV}, \eta=2.2
\text{Pt}(\mu^-) = 27 \text{ GeV}, \eta=0.7
Dielectron and 3 jets
Observed (expected) limits on the mass of the KK graviton in the bulk RS model are 630 (590) GeV