Exotics Searches in Jet Final States with the ATLAS Detector

Adam Gibson
University of Toronto
On behalf of the ATLAS Collaboration

EPS HEP 2011
July 21, 2011
Outline, Motivation

• Jet signatures probe the highest energies directly accessible at the LHC
• Test popular models like those with extra dimensions

• Model-independent, signature-based, searches for new physics
• Limits set on particular models including
  – Dijet resonances
  – Extra Dimensions, strong gravitational scenarios (ADD, black holes)
  – Compositeness models (e.g. excited quarks) and contact interactions
  – Model-independent limits

• Multi-jet searches ($\geq 5$ jets)
• Dijet searches ($\geq 2$ jets)
• Monojet searches (== 1 jet)
Outline, Motivation

- Jet signatures probe the highest energies directly accessible at the LHC
- Test popular models like those with extra dimensions

- Model-independent, signature-based, searches for new physics
- Limits set on particular models including
  - Dijet resonances
  - Extra Dimensions, strong gravitational scenarios (ADD, black holes)
  - Compositeness models (e.g. excited quarks) and contact interactions
  - Model-independent limits

- Multi-jet searches ($\geq 5$ jets)
- **Dijet searches ($\geq 2$ jets)**
- **Monojet searches ($\equiv 1$ jet)**

New results: Presented for the first time, today!
LHC and ATLAS Operations

- 2010: A solid start to physics operations
  - ATLAS papers with e.g. 36 pb\(^{-1}\)
- LHC has continued remarkable performance in 2011
- ATLAS subdetectors record good quality data
- ATLAS and LHC operations have already supported excellent physics in 2011
  - Brand new results with 0.81 and 1.0 fb\(^{-1}\)

Subdetector fraction of good data for 593 pb\(^{-1}\) recorded

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
<th>Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>SCT</td>
<td>TRT</td>
<td>LAr EM</td>
</tr>
<tr>
<td>99.8</td>
<td>99.5</td>
<td>100</td>
<td>89.3</td>
</tr>
<tr>
<td>LAr</td>
<td>HAD</td>
<td>FWD</td>
<td>LAr</td>
</tr>
<tr>
<td>92.7</td>
<td>94.3</td>
<td>99.5</td>
<td>100</td>
</tr>
<tr>
<td>Tile</td>
<td>MDT</td>
<td>RPC</td>
<td>CSC</td>
</tr>
<tr>
<td>100</td>
<td>99.5</td>
<td>100</td>
<td>99.9</td>
</tr>
<tr>
<td>Muon Detectors</td>
<td>TGC</td>
<td></td>
<td>Solenoid</td>
</tr>
<tr>
<td>98.5</td>
<td></td>
<td></td>
<td>Toroid</td>
</tr>
<tr>
<td>Magnets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>97.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at \(\sqrt{s} = 7\) TeV between March 13th and June 6th (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

July 21, 2011

A. Gibson, Toronto
Very high energy jet event

\[ m_{jj} = 4040 \text{ GeV} \]

\[ p_T^{j_1} = 1850 \text{ GeV} \]

\[ p_T^{j_2} = 1840 \text{ GeV} \]

ATLAS-CONF-2011-081
Search in Multi-Jet Final State: Black Holes?

- What if the Planck scale is approximately the same as the EW scale?
  - Large, flat, extra dimensions can allow it (ADD)
  - Gravity can become strong at the TeV scale, perhaps we’ll abundantly produce microscopic black holes at the LHC

- Assume classical black hole production, and semi-classical decays
  - (For this analysis.) Expected to hold well above the reduced Planck scale, \( M_D \).
    - We set the signal cross section to zero below a threshold mass \( M_{th} > M_D \).
  - Black hole quickly evaporates, decaying democratically according to number of degrees of freedom
    - Lots of quarks and gluons (jets), also all other particles

QCD peaks at low numbers of jets \( (N_J) \), and low \( \Sigma p_T \)

Black hole scenarios peak at high \( N_J \) and high \( \Sigma p_T \) (here Blackmax \( M_D = 1 \) TeV, \( M_{th} = 4.3 \) TeV, \( n = 2 \) extra dimensions)
Multi-Jet Search: New Physics? Or Set Limits

Require $E_{T1} > 250$ GeV for good trigger efficiency

For $N_J$, count jets with $p_T > 50$ GeV

To good approximation, the shape of $\Sigma p_T$ is the same in QCD for $N_J < 5$ and $N_J \geq 5$.

- Use $1.1$ TeV < $\Sigma p_T$ < $1.2$ TeV region for normalization, then compare the $N_J < 5$ shape to $N_J > 5$ data
- Predict number of events in signal region: $N_J \geq 5$, $\Sigma p_T > 2$ TeV
  - $3.7 \pm 1.0$ (stat) $\pm 1.1$ (syst) compared to 7 data
  - Largest syst is 24% due to QCD modelling
- At 95% CL cross section $\times$ acceptance $< 0.29$ pb
- Set model-dependent limits in $M_D$, $M_{th}$, $n$ space

A. Gibson, Toronto
Searches with a Dijet Signature, and Some Nuts and Bolts

- Also perform sensitive searches for new physics at highest pt using dijet events
  - $\geq 2$ jets, instead of $\geq 5$
- Look for “bumps” in the $m_{jj}$ distribution, and discrepancies in the dijet angular distributions
- Results presented today with 36 pb$^{-1}$
  - New Journal of Physics 13 (2011) 053044
- And new results, for the Dijet Mass Distributions, with 0.81/fb
  - ATLAS-CONF-2011-095
  - Expand on the experimental details for this latest search
- Require two high pt jets
  - Reconstructed with anti-$k_T$ algorithm, $R = 0.6$
  - Calibrated with MC-derived $p_T$ and $\eta$ dependent function
  - Apply “cleaning cuts” to remove events affected by non-collision backgrounds
    - Require $|y_1 - y_2| < 1.2$ and $|\eta| < 2.8$ to suppress QCD
    - For jet trigger efficiency, require $m_{jj} > 717$ GeV (effectively, $p_T^{j2} > 150$ GeV)
- 2011 data-taking brings a few new challenges
  - Significant in-time and out-of-time pileup; modeled in MC and MC re-weighted to match data
  - Small hole in central EM calorimeter (6 front end boards, O[1%]) warrants fiducial cut
Importance of Dijet Angular Information

- Both the resonance search and the angular search **take advantage of the angular distribution of dijets in background (QCD, relatively forward) vs. many signal hypothesis (e.g. q*, relatively central)**
  - Resonance analysis cuts on $|y_1 - y_2| < 1.2$
  - Angular analysis analyzes the angular distribution
    - Or analyzes $F_{\chi}$, the fraction of events with small $|y_1 - y_2|$, in bins of $m_{jj}$

\[ \text{QCD events in} \ 1 \ \text{pb}^{-1} \]
\[ \text{Signal events in} \ 1 \ \text{pb}^{-1} \]

ATLAS Preliminary

July 21, 2011
A. Gibson, Toronto
Dijet Resonance Search: Data and Background Fit

- Model-independent search for new physics
  - Do we see any bumps in $m_{jj}$, on top of a smooth background?

- Data fit well by the same QCD-compatible function in use for some time at the LHC and Tevatron
  \[ f(x) = p_1 (1 - x)^{p_2} x^{p_3 + p_4 \ln x} \]
  - Use $\chi^2$ test statistic, throw pseudo-experiments to evaluate p value in data, $p = 0.35$; reasonable background fit
  - Pseudo-experiments are Poisson fluctuations around background fit

- Can the fit absorb a signal?
  - Not easily, for a resonance
  - But, if $p < 0.01$ we exclude most discrepant region
  - Improves sensitivity, and greatly improves the fit if there’s a large signal
Do we find a dijet resonance? Ask BumpHunter

- Use BumpHunter (arXiv:1101.0390) to look systematically for candidate “bumps”
  - Two bins to half the width of the $m_{jj}$ distribution
  - Look for the candidate “bump” least consistent with smooth background
- Consider the Poisson $p$ value of the most discrepant bump
  - Compare to most discrepant bumps from pseudo-experiments (PE’s); thus account for “look elsewhere effect”
- In 2011 dataset, the most discrepant bump is two bins wide, 1162-1350 GeV
  - $p$ value of 0.62
  - Perfectly likely to get a bump as significant from a Poisson fluctuation of smooth bkgrd
  - No evidence for new physics 😊
No Evidence for New Physics in Dijet Mass Distribution: Set Limits

- For the “limit setting phase” we have specific models in mind (one theory, with fixed parameters, e.g. 2 TeV \( q^* \))
- Signal events with full detector simulation for \( m_{jj} \) templates
  - Background fit for limit setting uses signal template on top of smooth background function
- Bayesian limits: prior flat in signal cross-section
- Set limits on various models
  - \( q^* \) and axigluon limits nearly 1 TeV better than best published limits
  - New: scalar color octets
    - T. Han et al JHEP 12 (2010) 085

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL Limits (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>Excited Quark ( q^* )</td>
<td>2.77</td>
</tr>
<tr>
<td>Axigluon</td>
<td>3.02</td>
</tr>
<tr>
<td>Color Octet Scalar</td>
<td>1.71</td>
</tr>
</tbody>
</table>

- Also limits on simplified Gaussian models, for various means, widths – w/ systematics
  - Intended to ease application to other models

A. Gibson, Toronto
Dijet Angular Analysis: Chi

- Normalized spectra of $\chi = \exp(|y_1 - y_2|)$
  - Finely resolve angular distributions, coarse mass bins
  - Normalized so that systematics cancel (luminosity, bulk of jet energy scale)
  - Highest mass bin acts as a search bin
- Event selection very similar to $m_{jj}$ search
  - Consider also higher rapidity, lower $p_T$ jets and lower $m_{jj}$
- “Discovery Phase”
  - Compare data with NLO QCD prediction
  - Use $\chi^2$ as a test statistic, compare with pseudo-experiments
  - $p$ values 0.44, 0.33, 0.64, 0.89, 0.44
  - No evidence for new physics ☹️
New Dijet Angular Observable: $f_\chi(m_{jj})$

- $F_\chi(m_{jj}): \frac{N(|y_1-y_2| < 1.2)}{N(|y_1-y_2| < 3.4)}$
  - Coarse use of angular information: chi fraction $F_\chi$
    - Roughly, the fraction of events with central, “new physics”-like, jets
  - Resolve angular deviations with fine bins of $m_{jj}$; $F_\chi(m_{jj})$
  - Combine some strengths of the resonance analysis and the chi analysis

- Use bin-by-bin analysis to compare with NLO QCD prediction
  - Calculate p value from PE’s (0.28)
    - In QCD pseudo-experiments we see something more discrepant 28% of the time
    - Our data is consistent with statistical fluctuations around QCD
  - No evidence for new physics ☹

- Set limits using Bayesian and/or Frequentist approaches (likelihood ratio)
Summarizing ATLAS searches with dijets

- Several analysis techniques that make complementary use of dijet $m_{jj}$ and angular distributions
  - Unfortunately, no evidence for new physics
  - So, we set the world’s best limits instead (for $q^*$, axigluons, low multiplicity QBH)
- New $F_\chi(m_{jj})$ observable combines advantages of what were fairly separate methods
  - Continue to explore the best ways to slice this 2D space of observables ($m_{jj}$ and angular information)
- Limits on $q^*$ as a manifestation of quark compositeness
- Also consider contact interactions, as a low energy proxy for quark compositeness
- And low multiplicity Quantum Black Holes (QBH)
  - Near the Planck mass, $M_D$, it has been suggested that gravitational interactions might be dominantly _low_ multiplicity, e.g. dijets

Limits from 0.81 fb⁻¹

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL Limits (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>Excited Quark $q^*$</td>
<td>2.77</td>
</tr>
<tr>
<td>Axigluon</td>
<td>3.02</td>
</tr>
<tr>
<td>Color Octet Scalar</td>
<td>1.71</td>
</tr>
</tbody>
</table>

Limits from 36 pb⁻¹

<table>
<thead>
<tr>
<th>Model and analysis strategy</th>
<th>95% CL limits (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>QBH for $n = 6$</td>
<td></td>
</tr>
<tr>
<td>Resonance in $m_{jj}$</td>
<td>3.64</td>
</tr>
<tr>
<td>$F_\chi(m_{jj})$</td>
<td>3.49</td>
</tr>
<tr>
<td>$\theta_{np}$ parameter for $m_{jj} &gt; 2$ TeV</td>
<td>3.37</td>
</tr>
<tr>
<td>11-bin $\chi$ distribution for $m_{jj} &gt; 2$ TeV</td>
<td>3.36</td>
</tr>
<tr>
<td>Contact interaction $\Lambda$ $F_\chi(m_{jj})$ Bayesian</td>
<td>5.7</td>
</tr>
<tr>
<td>$F_\chi(m_{jj})$</td>
<td>5.7</td>
</tr>
<tr>
<td>$F_\chi$ for $m_{jj} &gt; 2$ TeV</td>
<td>5.2</td>
</tr>
<tr>
<td>11-bin $\chi$ distribution for $m_{jj} &gt; 2$ TeV</td>
<td>5.4</td>
</tr>
</tbody>
</table>
Monojets: a single jet plus missing $E_T$

- Another possible consequence of large extra dimensions (e.g. ADD)
  - Produce jet + Graviton, graviton disappears into the extra dimension
  - Observe a single (high $p_T$) jet and missing $E_T$
- Submitted to PLB based on 33 pb$^{-1}$ (http://arxiv.org/abs/1106.5327)
  - Search for new phenomena with the monojet and missing transverse momentum signature using the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions
  - Updated CONF note with 1 fb$^{-1}$
  - **First presented in public today!**
- Missing $E_T$ trigger
- Signal region (“HighPt”)
  - $p_T^{j1} > 250$ GeV, missing $E_T > 220$ GeV,
  - $p_T^{j2} < 60$ GeV, $\Delta\phi(j2, \text{missing } E_T) > 0.5$
  - No reasonable e’s, $\mu$’s
- Missing $E_T$ calculated from locally calibrated clusters of calorimeter cells
- Anti-$k_T$ 0.4 jets (calibration, cleaning much as in dijet search)
- Consider control regions with electrons or muons, and cross-check with “lowPt” and “veryHighPt” cuts
Monojet Background Predictions

- Dominant background is EW
  - “Irreducible” (Z → νν + jets) and single lepton + jets
  - EW normalization taken from data, applied to MC samples
- Multi-jet background estimated in data by reversing delta-phi cut and allowing a 2nd jet
Monojets: Determining the EW normalization

- Use a control sample, with one or more electrons or muons to normalize the EW background prediction
- Test the shape of the ALPGEN + NNLO k factor prediction vs. leading-jet $p_T$ threshold

- Normalization factors
  - $0.87 \pm 0.05$ for muons (used also for $Z \to \nu \nu$)
  - $0.81 \pm 0.09$ for electrons
No evidence for new physics: set limits

- Excellent agreement between data and the background prediction
  - 965 events vs. 1010 ± 37 (stat) ± 65 (syst);
  - Dominant systematic is normalization of EW background, a “good” systematic

- So, we set limits
  - Using the total number of events in the signal region
  - CLs, modified frequentist, statistical analysis

- Model-independent limit on cross section times acceptance
  - 0.11 pb, at 95% CL

- Using the acceptance from ADD signal samples (Pythia) obtain
  - 95% CL limit on fiducial cross section: 0.13 pb
Limits on Planck Scale, MD, for ADD extra dimensions

- Comparing to the ADD cross section, set limits as a function of the number of extra dimensions
  - Additional theory uncertainties 20%
  - ISR/FSR, scale, etc.
- Using (Pythia) low-energy effective theory version of ADD
  - Invalid for $\sqrt{s}$-hat > $M_D$
  - So, we interpret it carefully
- Extend the reach of previous limits
  - ATLAS, CMS, CDF, LEP

<table>
<thead>
<tr>
<th>$n$</th>
<th>expected [TeV]</th>
<th>observed [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.98</td>
<td>3.16</td>
</tr>
<tr>
<td>3</td>
<td>2.44</td>
<td>2.56</td>
</tr>
<tr>
<td>4</td>
<td>2.18</td>
<td>2.27</td>
</tr>
<tr>
<td>5</td>
<td>2.03</td>
<td>2.10</td>
</tr>
<tr>
<td>6</td>
<td>1.92</td>
<td>1.99</td>
</tr>
</tbody>
</table>
Conclusions

• LHC and ATLAS performing well!
• Sensitive searches for new physics with jet signatures
  – Multi-jet, Dijet, and Monojet
  – Probing the highest energies directly accessible at the LHC
  – And probing popular models, like those with extra dimensions
• Unfortunately, no evidence yet for new physics
  – Instead, set excellent limits on particular models, and model-independent limits
  – $q^*$, axigluons, scalar octets, contact interactions, Planck scale for black holes and extra dimensions
• Looking forward to lots of data and excellent discovery possibilities this year
• LHC center of mass energy can make a big difference for searches at high $p_T$
  – Especially for dijet searches
  – Would be great to run at 8 TeV, 9 TeV, or of course 14 TeV center of mass
• Hopefully some surprises, and new physics, are on the horizon!

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic
Related Presentations at EPS-HEP 2011

- Thorsten Alexander Dietzsch, poster
  - *Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at sqrt(s) = 7 TeV measured with the ATLAS Detector*

- Valerio Rossetti, poster
  - *Search for new physics in events with monojet and large MET with ATLAS detector*

- Dave Charlton (Monday plenary)
  - *Searches for new physics and highlights from ATLAS*

- Thorsten Kuhl (earlier today)
  - *Exotics Searches in Top, Top-like and Diboson Final States with the ATLAS Detector*

- Tetiana Hryn'ova (coming soon, in this session)
  - *Exotics Searches in Photon and Lepton Final States with the ATLAS Detector*

- Paolo Francavilla
  - *Measurement of single and multi-jet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with ATLAS*

- Dag Gillberg, poster
  - *Jet performance and inclusive jet cross section measurement in ATLAS*

- Caterina Doglioni
  - *Jet resolution and energy scale uncertainty in ATLAS*

- Andreas Salzburger
  - *Heavy Flavor Production in ATLAS*
**Muon Spectrometer** ($|\eta|<2.7$): air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

**Inner Detector** ($|\eta|<2.5$, $B=2T$): Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, $e/\pi$ separation
Momentum resolution: $\sigma/p_T \sim 3.8 \times 10^{-4} \ p_T (\text{GeV}) \oplus 0.015$

**3-level trigger** reducing the rate from 40 MHz to ~200 Hz

**EM calorimeter**: Pb-LAr Accordion
$e/\gamma$ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

**HAD calorimetry** ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing $E_T$
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

**Length**: ~ 46 m
**Radius**: ~ 12 m
**Weight**: ~ 7000 tons
~$10^8$ electronic channels
3000 km of cables
ATLAS Calorimeters

~180,000 cells in LAr calorimeter
~5,000 cells in Tile calorimeter

Up to four longitudinal samplings, each, for EM and hadronic.

Fine transverse and longitudinal segmentation.

\[ \eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right] \]
Very high energy mono-jet event
\( p_{T}^{j1} = 600 \text{ GeV}; \ p_{T}^{j2} < 30 \text{ GeV}; \) Missing \( E_{T} = 520 \text{ GeV} \)

ATLAS-CONF-2011-096

Run Number: 180309, Event Number: 36060682
Date: 2011-04-27 02:33:15 CEST