Dijet searches in ATLAS

Georgios Choudalakis
ATLAS Collaboration

*University of Chicago

DPF2011 @ Brown
August 10, 2011
Overview

Two complementary ways of analyzing dijet events:
- Dijet resonance search in $m_{jj}$.
- Dijet angular distribution analysis.

In this presentation:
- Flashback of 36 pb$^{-1}$ results [Latest dijet angular analysis].
- Dijet resonance search in $m_{jj}$ with 0.81 fb$^{-1}$.
- Some deeper discussion about:
  - Model-independent search [BumpHunter].
  - Model-independent limits.
Quick flashback to 36 pb$^{-1}$ results, the latest results of the dijet “angular” analysis.

From:
The observables of the angular analysis

The signal is expected in $|y_1 - y_2| < 1.2$, namely $\chi < 3.32$.

**Background:** Pythia QCD $\times$ $k$-factor from NLOJET++.

**Systematics:** Jet Energy Scale, $\mu_R$ and $\mu_F$, PDF.

$F_\chi = \text{fraction of events in } |y_1 - y_2| < 1.2.$
Summary of results with $36 \text{ pb}^{-1}$

<table>
<thead>
<tr>
<th>Analysis / observable</th>
<th>95% C.L. Limits (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td><strong>Excited Quark $q^*$</strong></td>
<td></td>
</tr>
<tr>
<td>Resonance in $m_{jj}$ [Bayesian]</td>
<td>2.07</td>
</tr>
<tr>
<td>$F_\chi(m_{jj})$ [Frequentist]</td>
<td>2.12</td>
</tr>
<tr>
<td><strong>Randall-Meade Quantum Black Hole for $n = 6$</strong></td>
<td></td>
</tr>
<tr>
<td>Resonance in $m_{jj}$ [Bayes.]</td>
<td>3.64</td>
</tr>
<tr>
<td>$F_\chi(m_{jj})$ [Freq.]</td>
<td>3.49</td>
</tr>
<tr>
<td>$F_\chi$ for $m_{jj} &gt; 2 \text{ TeV}$ [Freq.]</td>
<td>3.37</td>
</tr>
<tr>
<td>$\frac{dN}{d\chi}$ for $m_{jj} &gt; 2 \text{ TeV}$ [Freq.]</td>
<td>3.46</td>
</tr>
<tr>
<td><strong>Axigluon</strong></td>
<td></td>
</tr>
<tr>
<td>Resonance in $m_{jj}$ [Bayes.]</td>
<td>2.01</td>
</tr>
<tr>
<td><strong>Contact Interaction $\Lambda$</strong></td>
<td></td>
</tr>
<tr>
<td>$F_\chi(m_{jj})$ [Freq.]</td>
<td>5.7</td>
</tr>
<tr>
<td>$F_\chi(m_{jj})$ [Bayes.]</td>
<td>5.7</td>
</tr>
<tr>
<td>$F_\chi$ for $m_{jj} &gt; 2 \text{ TeV}$ [Freq.]</td>
<td>5.2</td>
</tr>
<tr>
<td>$\frac{dN}{d\chi}$ for $m_{jj} &gt; 2 \text{ TeV}$ [Freq.]</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Three observables used in the angular analysis:
- Whole $F_\chi(m_{jj})$ spectrum
- $F_\chi$ for $m_{jj} > 2 \text{ TeV}$
- $\frac{dN}{d\chi}$ in 11 $\chi$ bins, for $m_{jj} > 2 \text{ TeV}$
On to some new results now, from the dijet resonance search in $m_{jj}$. 
Resonance search in dijet mass

\[ \frac{d\sigma}{d m_{jj}} \]

QCD

New Physics

Background determined by (smart) fitting

\[ f(x) = p_0 \frac{(1-x)^{p_1}}{x^{p_2} + p_3 \ln x}, \quad x \equiv \frac{m_{jj}}{\sqrt{s}}. \]
About the function \( f(x) = p_0 \frac{(1-x)^{p_1}}{x^{p_2+p_3} \ln x}, \quad x \equiv \frac{m_{jj}}{\sqrt{s}} \)

- Able to fit wonderfully **Pythia QCD, Alpgen, Herwig, NLOJET++**.
- No inflection points. [Unable to fit big bumps.]
- \( f(m = \sqrt{s}) = 0 \). [A physical property.]
- It is a parabola in log-log scale, except for the numerator which is added to make it go to 0 at \( \sqrt{s} \).
- Known, and used several times before. [e.g., CDF, Phys.Rev.D 79 (2009) 112002].

\[
\sqrt{s} = 7 \text{ TeV} \\
\bullet \text{ Pythia QCD} \\
\text{Fit}
\]

Events/(bin width) [Events/GeV]

Reconstructed \( m_{jj} \) [GeV]
Event selection

- The obvious: Stable beams, good detector conditions, good vertex, etc.
- $m_{jj}$ in trigger plateau. [$>717$ GeV]
- Two leading jets be of good quality. [well-measured, away from bad calorimeter regions.] Cost: $\sim 3.7\%$, due to temporary “hole” in calorimeter.
- No other jet of poor quality that has $p_T > 0.3p_T^2$. [Avoid accidental re-ordering of jets in $p_T$.] Cost: 0.3%, and would be 0 if it was not for the “hole”.
- $|\Delta y| < 1.2$ [Suppress $t$-channel QCD background.]

ATLAS Preliminary

$\int L dt = 0.81$ fb$^{-1}$, $\sqrt{s} = 7$ TeV

Trigger efficiency plateau of the 1st unprescaled single-jet trigger. [j180].

Reconstructed $m_{jj}$ [GeV]

Efficiency

Efficiency

Reconstructed $m_{jj}$ [GeV]
Suppression of QCD background

Great sensitivity boost, by selecting central events.

[This coheres with dijet angular analysis, where \( F_\chi \) is, practically, the fraction of events passing this cut.].
The fit, overall, is fantastic: The $p$-value of the ($-\log L$) statistic is about 13%.
Event at $m_{jj} = 4$ TeV

Both jets at $p_T \approx 1.8$ TeV.
The **BumpHunter** hypertest is used to look for excesses

Hypertests, and the BH in specific, are explained in arXiv:1101.0390 [physics.data-an].

What does it do, in brief?

- It counts events in all intervals, and computes Poisson p-values.
- It keeps the smallest Poisson $p$-value it finds.  [This is the BH’s “test statistic”.
- It generates several 0-signal pseudo-experiments and scans them too.
- It counts how often a pseudo-spectrum would have any interval that is more significantly discrepant than the one observed in the data.  [This is the BH’s $p$-value.]

So, what’s the point of all this?

- All particular tests combined into one hypertest.  [What makes it a hypertest is that its test statistic is not just a metric of discrepancy (like $\chi^2$), but the smallest from an ensemble of $p$-values.]
- Hypertests account for the trials factor. The BH is aware that many intervals were tried, and its $p$-value reflects that.
- Sensitive to excesses, without presuming their shape or location.
- It’s just one hypertest.  Obvious generalizations, e.g. TailHunter.
A demo of sensitivity
Toy MC used; no ATLAS data involved.

Gassian signal is injected, as shown here [At 1000±50 GeV]:

We find the probability of making a claim, as a function of expected signal.

The BumpHunter [followed by the TailHunter], is more sensitive than other tests to this signal. The absolute winner [black] is “cheating”: It knows a-priori the signal shape and location.
The search phase of the analysis

The most significant excess found in the data.

All mass intervals, and their Poisson $p$-values, are summarized in this "tomography" plot.
The search phase of the analysis

The p-value of the BUMPHUNTER statistic is 62%.

Totally insignificant.
Systematic uncertainties

- **Jet Energy Scale**: From 2 to 4% at $p_T$ above 100 GeV.
- **Jet Energy Resolution**: 5% relative uncertainty. Negligible impact on limits.
- **Fit uncertainty**: Ranges from $< 1\%$ at 1 TeV, to $\sim 20\%$ at 4 TeV.
- **Luminosity uncertainty**: 4.5%

**Overlaid JES variations, from $-3\sigma$ to $+3\sigma$.**

**Overlaid JER variations, from $-3\sigma$ to $+3\sigma$.**
Limits to specific models

At 95% credibility level, with constant priors:

\[ m_{q^*} > 2.91 \, \text{TeV}. \]  
\[ m_A > 3.21 \, \text{TeV}. \]  
\[ m_{s8} > 1.91 \, \text{TeV}. \]  

[expected 2.77]  
[expected 3.02]  
[expected 1.71]
Limits to Gaussian signal templates

- Gaussian “signals”, of various means and widths.
- Approximation to virtually any resonance.
- Systematic uncertainties included, just like for specific models.
Demonstration: approximating $q_{1.5}^* \text{TeV}$ with a Gaussian

The two reasons this approximation works:

1. Limit of Gaussian $\approx$ Limit of chopped template.
2. Limit $\propto$ acc/nce of chopping $\Rightarrow$ same mass limit, no info. lost.
Summary

- Reviewed the results from 36 pb$^{-1}$ of 2010.
- Updated the dijet resonance search in $m_{jj}$ with 0.81 fb$^{-1}$ of data.
- Model-independent search (BUMP Hunter) found no significant discrepancy.
- Updated limits to benchmark models, like $q^*$. (2.91 TeV)
- Added scalar octet to the repertoire.
- Updated model-independent limits.

Our reach extended by about 1 TeV.
Backup

Motivation
Fitting Pythia
Smart fit
Demo of model-independent limits
Model details
Old plots
Why inclusive dijet searches?

- Well... because it’s such an obvious thing to do!  
  [Devil is in the detail.]

- Theoretical reasons:
  - $q^*$ [our “benchmark”]
  - Axigluons, colorons, techni-mesons, etc.
  - Extra dimensions (e.g. Randall-Sundrum graviton, Quantum Black Holes, etc.)
  - Even String theory!
  - ... and the list goes on...

- Experimental reasons:
  - Superior hadronic calorimetry.
  - Few %-level JES uncertainty  
    [Accurate ATLAS MC, and in-situ calibration.]
  - Low sensitivity to pile-up etc.

- Analytic reasons:
  - Large SM statistics $\Rightarrow$
  - Data-driven background estimation.
  - Very high energies, from early on.  
    [World-best results with just 0.3 pb$^{-1}$ of data.]
Fitting Pythia QCD with \( f(x) = p_0 \frac{(1-x)^{p_1}}{x^{p_2+p_3 \ln x}} \), \( x \equiv \frac{m_{jj}}{\sqrt{s}} \)

\( \sqrt{s} = 7 \text{ TeV} \)

\begin{itemize}
  \item Pythia QCD
  \item Fit
\end{itemize}

**ATLAS** Preliminary

Reconstructed \( m_{jj} \) [GeV]

Lower masses

Reconstructed \( m_{jj} \) [GeV]

Higher masses

Georgios Choudalakis (U.Chicago)
Smart fit

To prevent potential signal from biasing the fit, we have an anti-bias mechanism.

If the first fit gives a $\chi^2 p$-value $< 0.01$, we search for windows to omit from the fit, trying to make the fit better in the sidebands.

The window search is similar to how the BUMP$\text{HUNTER}$ looks for the signal.

If a window is found that makes the $\chi^2$ $p$-value $> 0.01$, we stop. If not, we exclude the window that does the best job.

The result is that the signal is better defined, and easier to see, because we fit just the sidebands.

This didn’t do anything when fitting the data, but in pseudo-experiments it could kick in.

Demonstration: approximating $s82 TeV$ with a Gaussian

The two reasons this approximation works:

1. Limit of Gaussian $\simeq$ Limit of chopped template.
2. Limit $\propto$ acc/nce of chopping $\Rightarrow$ same mass limit, no info. lost.
Model details

Excited quark ($q^*$)
- $qg \rightarrow q^* \rightarrow qg$, with SM-quark-like couplings, and compositeness scale $\Lambda = m_{q^*}$.
- Pythia $\rightarrow$ ATLAS sim.
- MRST2007LO* PDF [MC10 tuning, ATLAS-CONF-2010-031].

Scalar octet ($s_8$)
- Taken from arXiv:1010.4309, by Tao Han et al.
- Like a spin-0 heavy gluon.
- MadGraph $\rightarrow$ Pythia $\rightarrow$ ATLAS sim.
- Used CTEQ6L1 PDFs [MC09’ tuning, ATLAS-PHYS-PUB-2010-002].

Axigluon ($A$)
- CalcHEP
- MRST2007LO* PDF
- Acceptance obtained from parton-level kinematic cuts, plus chopping at $[0.7m_A,1.3m_A]$.
- Verified, using ATLAS sim., that the chopped $A$ gives very similar limits to the full $q^*$ template, so, instead of using actual $A$ templates, we use observed limits from $q^*$ templates.
  [Similar treatment of $A$ have been used before. E.g. CDF, Phys.Rev.D 79 (2009) 112002, or CMS PhysRevLett.105.211801, and more recent works.]
Comparison of signal templates

![Graph showing comparison of signal templates with two lines representing q* and s8 for reconstructed m_{jj} [GeV] with probabilities on a log scale.]

- q*
- s8

m = 2000 GeV
BSM lagrangian densities

**Excited quark**

\[ L_{gqq^*} = g_{QCD} \frac{f_s}{4\Lambda} \bar{q}_R^* \sigma_{\mu\nu} \lambda_{\alpha} G_{\mu\nu}^{\alpha} q_L, \quad f_s \to 1, \quad \Lambda \to m_{q^*}. \]

**Axigluon**

\[ L_{Aq\bar{q}} = g_{QCD} \bar{q} A_{\mu}^{\alpha} \frac{\lambda_{\alpha}}{2} \gamma^\mu \gamma^5 q. \quad A \to gg \text{ forbidden by Parity.} \]

**Scalar (color) octet**

\[ L_{gg8} = g_{QCD} d^{ABC} \frac{\kappa_s}{\Lambda_s} S_8^A F_{\mu\nu}^B F_{C,\mu\nu}, \quad S_8=\text{scalar octet}, \quad \kappa_s = \text{coupling} = 1, \]
\[ g_{QCD}^2 = 4\pi \alpha_s, \quad d^{ABC}=SU(3) \text{ isoscalar factor, } F_{\mu\nu}=\text{SM gluons tensor.} \]

**Quark contact Interaction**

\[ L_{qqqq} = \frac{\xi g^2}{2\Lambda^2} \bar{\psi}_q^{\mu} \psi_q^{\mu} \bar{\psi}_q \gamma_{\mu} \psi_q, \quad \frac{g^2}{4} = 1, \quad \xi = +1 \text{ (destructive interference).} \]
**Dijet $m_{jj}$ limits with 36 pb$^{-1}$**

![Graph showing ATLAS Dijet searches](image)

**ATLAS**

$\int L dt = 36 \text{ pb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$
Angular analysis, in 36 pb$^{-1}$

- Systematic uncertainties: Jet Energy Scale, $\mu_R$ and $\mu_F$, PDF
- Agreement between data and background:
  - The p-value of the likelihood test in $\frac{dN}{d\chi}$ is $> 30\%$ in all $m_{jj}$ bins.

Example of Neyman construction, using $F_{\chi}(m_{jj} > 2 \text{ TeV})$, to set QBH limits

\[
\int L\, dt = 36\, \text{pb}^{-1}, \sqrt{s}=7\, \text{TeV} \\
\theta_{\text{np}} > 2\, \text{TeV} \\
95\% \text{C.L. on } F_{\chi} \\
\text{Measured } F_{\chi} \\
\text{QCD prediction} \\
\text{expected limit contour (68\%)}
\]

\[
\int L\, dt = 36\, \text{pb}^{-1}, \sqrt{s}=7\, \text{TeV} \\
\sigma_{\text{QBH}} \times A_{\text{QBH}} \text{ [pb]} \\
\text{Expected Limit} \\
\text{Measured Limit}
\]

\[
\text{ATLAS} \\
\theta_{\text{np}} \\
\text{ATLAS} \\
M_D [\text{GeV}] \\
n = 2, n = 4, n = 6
\]