Search for New Physics in Boosted Topologies

Jim Cochran
Iowa State University
On behalf of the ATLAS & CMS Collaborations
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• Challenges
• Techniques
  – Jet Grooming
  – Observables
  – Validation
• Selection of Results
  – CMS: VV → qq qq (jet jet)
  – ATLAS: ZV → llqq
  – CMS: WV → lνqq
  – ATLAS: tt resonance search
  – CMS: tH → bqqbb
• Summary & Outlook
• LHC Run II: $E_{\text{com}} = 13$-$14$ TeV
  – BSM theories predict resonances with mass $\sim$ TeV
  – Many of these are expected to decay to dibosons, $t\bar{t}$, …
  – Due to high mass, these $W,Z,t,H$ will be at very high $p_T$ ($\gg m$)
    • and their decay products will be strongly boosted

  – Traditional reconstruction techniques relying on one-to-one jet-to-parton assignment will be inadequate
Techniques

• New techniques have been developed that reconstruct jets of a much larger radius
  – The internal structure can select such jets and can provide identification of the boosted objects

\[ m_{\text{jet}} \sim m_W \sim 80 \text{ GeV} \]

\[ + \text{Dipolar structure} \]

\[ m_{\text{jet}} \sim m_q \sim 0 \]

New observables: pruned jet mass, momentum balance \( (\sqrt{y_f}) \), N-subjettiness \( (\tau_N) \)
Jet Grooming

Reinterpretation of the jet to improve resolution of jet substructure measurements, reduce background and impact of underlying event & pile-up

Three related techniques:

- **Trimming**
  
  ![Trimming Diagram]
  
  Compares $p_T$ (constituents) with $p_T$ (jet) – removes soft components which are primarily from UI & PU

- **Filtering**
  
  ![Filtering Diagram]
  
  Remove constituents that are outside of subjets

- **Pruning**
  
  ![Pruning Diagram]
  
  Similar to trimming but occurs during jet reconstruction ⇒ does not require subjet reconstruction
Observables

- Single jet mass \( m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2} \)
  - Deduced from four-momentum sum of all jet constituents
    - Before and after any grooming
    - Can be reconstructed for any meaningful jet algorithm

- momentum balance \( \sqrt{y_f} = \min(p_{T}^{j1}, p_{T}^{j2}) \Delta R_{12} / m_{12} \)
  - Where \( p_{T}^{j1} \) and \( p_{T}^{j2} \) are the transverse momenta of the two leading subjets, \( \Delta R_{12} \) is their separation and \( m_{12} \) is their mass
  - To suppress jets from gluon radiation and splitting, \( \sqrt{y_f} > 0.45 \)

- \( N \)-subjettiness
  - Measures how well jets can be described assuming \( N \) sub-jets
    - Degree of alignment of jet constituents with \( N \) sub-jet axes
  - Sensitive to two- or three-prong decay versus gluon or quark jet
    - Highest signal efficiencies from \( N \)-subjettiness ratios \( \tau_{N+1}/\tau_{N} \) (\( \tau_{N+1/N} \) or \( \tau_{N+1,N} \))
    - For most analyses in this talk (\( W/Z \rightarrow qq \)) will use \( \tau_{2/1} \)
Validation (using SM processes)

Boosted single W

ATLAS

$\sqrt{s} = 7$ TeV, $4.6$ fb$^{-1}$

$p_T > 320$ GeV, $|y| < 1.9$

$L > 0.15$

arXiv: 1407.0800v1
CMS: VV $\rightarrow$ qq qq (1)

- Benchmark models
  - Randall-Sundrum Graviton ($G_{RS} \rightarrow WW/ZZ$)
  - Bulk Graviton ($G_{BULK} \rightarrow WW/ZZ$) [ATLAS refers to this as $G^*$]
  - Extended Gauge Model $W'$ ($W' \rightarrow WZ$)

- Choose hadronic decay channel ($W/Z \rightarrow qq$)
  - Larger BR than fully- & semi-leptonic channels

- Must suppress (large) di-jet background
  - Use jet-substructure tagging techniques
    - Tag jets as $W/Z$-like or not

- Look for bump in the VV mass spectrum
Pruned-jet mass and N-subjettiness ratio $\tau_{21}$ provide excellent discrimination against di-jet background.

Each W/Z jet is classified as High Purity (HP) [$\tau_{21} \leq 0.5$] or Low Purity (LP) [$0.5 < \tau_{21} < 0.75$]. (HP, HP) events are classified as HP; (HP, LP) are classified as LP.
Di-jet mass spectrum shows no excess above background
- background obtained from fit to data with a smoothly falling function
- searched for peak on top of the background using maximum likelihood function
First limits on $G_{RS} \to WW$ and $W' \to WZ$ in the all-jets final state

$M(G_{RS}) > 1.2 \text{ TeV}$  

$M(W') > 1.7 \text{ TeV}$

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• Benchmark models
  - Kaluza-Klein Graviton ($G^* \rightarrow ZZ$)
  - Extended Gauge Model $W'$ ($W' \rightarrow WZ$)
[CMS refers to this as $G_{\text{BULK}}$]

• Choose semi-leptonic decay channel ($Z \rightarrow ee/\mu\mu$)
  - Larger BR than fully leptonic
  - Less background than fully hadronic

• Three selection approaches depending on resonance mass
  - Merged [very high $p_T$] (one large-R jet)
  - High $p_T$ resolved (two small-R jets)
  - Low $p_T$ resolved (two small-R jets)
• Boosted leptonic Z decays
  – the leptons are boosted and interfere with each other’s isolation cones
  – solution: subtract the other lepton’s $p_T$ from the isolation cone
  • Up to 50% gain in acceptance
• **Boosted Hadronic W/Z decays**
  
  - the two quarks merge into a single (fat) jet
  - Cut on mass of jet and momentum balance between subjets ($\sqrt{y_f}$) to reject background

![ATLAS: ZV → llqq (3)](image_url)
ATLAS: $ZV \rightarrow llqq (4)$

No significant deviations from SM expectations
ATLAS: ZV → llqq (5)

95% CL set using likelihood fit:

\[ M(G^*) > 730 \text{ GeV} \]

\[ M(W') > 1.6 \text{ TeV} \]

Significant improvement over previous limits
- 40% improvement due to luminosity increase \( (7\rightarrow 20 \text{ fb}^{-1}) \)
- 40% improvement at high mass due to new (boosted) techniques(!)

CMS llqq result at end of next section
• Benchmark models  
  [ATLAS refers to this as G*]  
  – Bulk Graviton Model ($G_{\text{BULK}} \rightarrow WW$)  
  – None used for $X \rightarrow WZ$

• Pursue both model-dependent & -independent limits

• Choose semi-leptonic decay channel ($W \rightarrow l\nu, Z \rightarrow qq$)  
  – Larger BR than fully leptonic  
  – Less background than fully hadronic

• Again use jet-substructure tagging techniques  
  – Tag jets as W/Z-like or not  
  – As with CMS VV $\rightarrow qq \, qq$ analysis, distinguish 2 V-jet categories  
    • High Purity (HP) [$\tau_{21} < 0.5$]  
    • Low Purity (LP) [$0.5 < \tau_{21} < 0.75$]
CMS: $WV \rightarrow l\nu qq$ (2)

- Require $65 < m_{\text{jet}} < 105$ GeV
- $p_T^{W\text{-jet}}$ and $N$-subjettiness ratio $\tau_{21}$ provide excellent discrimination against background
No excess beyond SM expectations was observed

With current luminosity, sensitivity is insufficient to set limits on the Bulk graviton models

For model-independent analysis

- reinterpret analysis as generalized search for $X \rightarrow WV$ with width $\Gamma_X$
- Resulting in 95% exclusion limits in the $M_X \times \Gamma_X$ plane
• Benchmark models
  – Topcolor [narrow width] (leptophobic $Z' \rightarrow \bar{t}t$)
  – Kaluza-Klein gluon in RS models [broad width] ($g_{KK} \rightarrow \bar{t}t$)
• Choose semi-leptonic decay channel ($\bar{t}t \rightarrow WbWb \rightarrow l\nu b\bar{b}q\bar{q}$)
  – Larger BR than fully leptonic
  – Less background than fully hadronic
• Jets are classified as either small radius ($R = 0.4$) or large ($R = 1$)
  – $p_T$ (small-R jets) $> 25$ GeV
  – $p_T$ (large-R jets) $> 300$ GeV
• $M(\bar{t}t)$ spectrum is tested for any excess beyond SM
• $\bar{t}t$ events are reconstructed in two modes
  – Resolved: Hadronic top identified as 2 or 3 small-R jets
  – Boosted: Hadronic top identified as 1 large-R jet
Combining both reconstruction modes, no excess is seen in the $M(t\bar{t})$ spectrum.
Resulting limits on cross section can be translated to limits on $M(Z')$ and $M(g_{KK})$

A narrow lepto-phobic topcolor $Z'$ is excluded at the 95% CL for $0.5 < M(Z') < 1.8$ TeV

A broad Kaluza-Klein gluon is excluded at the 95% CL for $0.5 < M(g_{KK}) < 2.0$ TeV
CMS: $tH \rightarrow bqqb\bar{b}$ (1)

- Benchmark model
  - Vector-like $T$ quarks (produced in pairs)
- $T$ expected to be very heavy $\Rightarrow$ very significant boost
- Based on previous tools, build top & Higgs jet taggers
  - which include subjet b-tagging
- Incorporate taggers into overall analysis
  - Optimization found best discrimination using $H_T$ and $m_H$
• $H_T$ and $m_H$ are combined into a likelihood discriminant
• Events are categorized based on number of Higgs-jet tags (1 or 2)
• Comparison with data finds no excess beyond SM expectations

$$m(T) > 747 \text{ GeV}$$
Summary & Outlook

• ATLAS & CMS have developed new techniques to identify highly boosted Vector Bosons & top quark jets
  – robust in high pile-up environment
  – product of intense experiment/theory collaboration
  – still under very active development
  – ATLAS & CMS are converging on common choices/definitions

• They have used these tools to search for BSM signatures
  – I have shown only a few recent results

• Run II will have higher energy (⇒higher boost)
  – these techniques (& their descendents) are crucial and will play a major role in SM measurements & BSM searches/discoveries(!!)