Search for $W' \rightarrow Xh \rightarrow qqbb$

Resonances

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CERN

- Established in 1954
- “The purpose of the European organization for nuclear research, is to further collaboration in scientific research of a purely fundamental nature” – CERN library
- Currently has 22 member states
- Home to the LHC and many other collider experiments
The Large Hadron Collider

- The LHC straddles the Swiss-French border
- Four experiments use p-p collisions from LHC
  - ALICE, ATLAS, CMS, and LHCb
- 27 km ring consisting of 1232 dipole magnets
A Toroidal LHC ApparatuS (ATLAS)

- One of two detectors on the LHC ring that employ a general search
- Searches range from discovery of the Higgs to beyond the SM
- Consists of 6 sub-detectors
- Weighs a total of 7,000 tonnes
ATLAS breakdown

- 46 meters long, 25 meters in diameter
- Inner detector
  - Pixel detector
  - SCT
  - TRT
- Solenoid magnet
- Calorimeters
  - EM Calorimeter
  - Hadronic Calorimeter
- Muon Spectrometer
The Standard Model

- Currently the most used model of particle physics
  - The model is lacking in many areas
- Describes the Weak, Strong, and EM forces
- Only about 4% of our known universe
- It describes well some ranges of the particle physics
The Standard Model

Fermions

- Particles with half integer spin
- Three generations increasing in rarity and energy
- Quarks
  - Interact via the strong force
  - Carry charge and hyper charge
  - Combine to form hadrons
- Leptons
  - Electron, Muon, and Tau interact via EM
  - Neutrinos interacted only via the weak force
The Standard Model

Bosons

○ Whole integer spin
○ Gauge bosons act as force carriers
○ The Photon and Gluon are the only known massless particles
  ○ mediate the weak force between all fermions
  ○ half-life = $3 \times 10^{-25}$ s.
○ The Higgs Boson ($\sim 125$ GeV)
Resonance and Decay

- Resonance is a peak at a particular mass point resulting from examining the cross section of a particle decay as a function of mass.
- This peak we observe is called as the resonance
  - This peak can either be a particle, or the resonance itself
- The invariant mass is the same as the rest mass ($m_0$) of a particle; this quantity is the same in any frame of reference, where it is calculated from energy and momentum.

\[ m_0^2 = E^2 - \left\| p^2 \right\| \]
Defining ATLAS Coordinates

- The $Z$-axis is labeled in the direction of the beam pipe
- Using cylindrical coordinates $(r, z, \varphi)$
- $\eta$ is pseudorapidity
  - where $\eta = -\ln(\tan(\theta/2))$
  - $\theta$ being the angle from the $z$-axis, and $\varphi$ is the azimuth angle from the beam pipe
- Angular separation between two points is defined as $\Delta R$
  - Where $\Delta R = \sqrt{\eta^2 + \varphi^2}$
Search for Xh (W’) Resonance

- The predicted particle hadronically decays into two bosons $W' \rightarrow Xh$
- The two bosons further decay, hadronically, to two bottom quarks and two others
  - $Xh \rightarrow qqbb$, or $h \rightarrow bb$ and $X \rightarrow qq$ (where $q$ is any quark)
Jet Reconstruction

- Following the p-p collision, jets are created from the high energy constituents
  - When $p_T$ of the particle is high then the decay products are high boosted
  - The Anti-$k_T$ algorithm, used in jet reconstruction, compares the $p_T$ and minimum $\Delta R$ on groups of jets
  - Classifies boosted jets
  - Regular jets ($R=0.4$), large-R jets ($R=1.0$), and track jets ($R=0.2$)
Large-R Jets

- Large-R jets form closely together and are composed of many smaller jets
- Track-jets are built by clustering Inner Detector tracks with $p_T > 500$ MeV using the Anti-$k_T$ algorithm with a small-R parameter of 0.2
- Observing the substructure of the large-R jet can tell us more information about the particles that created them
Jet substructure

- The $D_2$ is defined as follows:

$$D_2^{B=1} = E_{CF3}(E_{CF1}/E_{CF2})^3$$

- Where $E_{CF}$ are the energy correlation functions which are representations of the jet’s $i$-th constituents, pairs and triplet of constituents.

$$E_{CF1} = \sum_{i} p_{ti}$$
$$E_{CF2} = \sum_{ij} p_{ti} p_{tj} \Delta R_{ij}$$
$$E_{CF2} = \sum_{ijk} p_{ti} p_{tj} p_{tk} \Delta R_{ij} \Delta R_{jk}$$

- Since our X candidate should have a two body decay, we utilize the $D_2$ substructure cut
  - The $D_2$ identifies two prong structures of the large-$R$ jets (50% working efficiency)
  - Our X and h bosons decay into two quarks, implying a two prong structure
b-jet Selection

○ Our candidate Higgs boson decays into two b-jets
○ Utilizing the prolonged life time of bottom quarks, the vertex created by their decay is observed further from the original
  ○ This process is called b-tagging
○ Applying a cut that requires the MV2c10 > 0.3706 we select these as b-jets at an 77% working efficiency.
Event Selection

- First, one large-R jet must have a $p_T > 450$ GeV
  - Then, both jets have to pass a cut of $p_T > 250$ GeV
  - Along with a mass cut above 50 GeV
- The highest two $p_T$ large-R jets are selected as candidates for Xh decay
- We further analyze the substructure of the leading and sub-leading jets to classify the bosons
- The Higgs jet mass to fall within the 95 – 145 GeV and at least 1 b-jet
- The X boson’s mass is unknown and only for the interpretation of the results slices of $m_X$ are selected
- Lastly, the $D_2$ cut is also applied to the X candidate
Event Selection: Ambiguity Cases

- If both large-R jets fall within the Higgs mass range
  - The jet with more b-tagged track-jets is selected as the Higgs
- If both large-R jets fall within the Higgs mass range, and have the same amount of b-tagged jets
  - The higher $p_T$ large-R jet is selected as the Higgs
Search for Xh Resonance

- Beginning with a few plots run on signal serves as a method to test the analysis code. Properties of the signals are presented in the next slides.
- The preliminary tests were executed using the following signal:
X boson Selection

$\rho_T$ of X  

mass of X  

$\eta$ of X
Xh Selection

\( p_T \) of Xh

\( \eta \) of Xh

mass of Xh
X mass windows

- Since the X particle has an unknown mass, we choose to look at it in slices.
- Each one of the windows is selected by taking into account the estimated mX resolutions each window size is set to be at least equal to double the resolution size at the center of the window.
- The windows are allowed to overlap, however they are treated independently.
X mass windows

- The windows from 500-1000 GeV for 1 b-jet and 389.5-1000 GeV for 2 b-jets are merged due to lack of data.
- The resulting windows are as follows:
  - **Both 1 and 2 b-jets:** 50-80, 57.5-87.7, 65-97, 73-105, 81-113, 89-123, 97.5-131.5, 106-142, 115-151, 124-160, 133-171, 142.5-180.5, 152-192, 162-202, 172-214, 182.5-224.5, 193-237, 204-248, 215-261, 226.5-272.5, 238-286, 250-300, 262.5-312.5, 275-327, 288-340, 301-355, 314.5-370.5, 328.5-386.5, 343-403, 358-420, 373.5-437.5,
  - **2 b-jets:** 389.5-1000
  - **1 b-jet:** 389.5-457.5, 406.5-476.5, 424-496, 442-516, 460.5-538.5, 480-560, 500-1000
User Defined Fit

- Using a combination of two fits (6 parameters) the goal is to identify a signal peak above the background.
- The smoothly falling background fit in the VV -> JJ search [link](http://cds.cern.ch/record/2206137)

\[
\frac{dN}{dx} = p_0(1 - x)^{p_1 - \xi}p_2\cdot x^{-p_2}
\]

- The Lorentzian peak function defined as follows

\[
\frac{1}{\pi}\frac{\frac{1}{2}p_3p_4}{(x-p_5)^2 + (\frac{1}{2}p_4)^2}
\]

- The combination of these two successfully identifies signal over the background
User Defined Fit

- Here we can see how the combination of the background and Lorentzian fits an injected signal
- Signal: $m_{W'} = 3$ TeV
Binning

- To optimize the binning for every $m_X$ window the resolution of $m_W$ is used.
- The bins are chosen to be at least equal to the signal mass resolution and to contain expected background events with relative expected background uncertainty less than 75%.
- Only $m_W$ masses in the range between 1.2 - 4.0 TeV are interpreted, with the overflow included in the highest bin.
- In the high $m_X$ region the first bins would be in the resolved regime, and are dropped.
X Windows with Fit
X Windows with Fit
X Windows with Fit
The stability of the parameters seems to decrease as the X windows increased in mass.
Conclusions

- We were able to successfully classify large-$R$ jets as our candidate bosons, using signal and data, while implementing selections in cases of ambiguity.
- With observations in many different mass windows for the $X$ as well as both one and two $b$-jet regions, the user defined fit function did not identify any resonance above the background.
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50–105 GeV
81–142 GeV
115–180.5 GeV
152–224.5 GeV
238–312.5 GeV
268–386.5 GeV
373.5–457.5 GeV
406.5–1000 GeV