Studies of Top Quark Decay Kinematics

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Abstract: The Standard Model is the theory that describes the fundamental particles and forces that govern our universe. The Higgs Boson is an elementary particle that is an excitation of the Higgs Field, which gives particles mass. Quarks are elementary particles that combine with others to make composite particles. The top quark is the heaviest quark. If the Higgs boson is made of undiscovered constituent particles, it is likely that the top quark is also made of similar particles based on how strongly they interact. In this case, events with four top quarks would be produced in excess of predictions from current theories. The purpose of this project is to study top quark kinematics to determine how to distinguish between background and signal top decays. A simulation (MADGRAPH) was used to generate events where t and $\bar{t}$ decay to a bottom quark and a W boson, and the W bosons decay to $q\bar{q}$. Analysis shows that as the top quark's transverse momentum increases, the distance between the top quark and its decays decreases. This decrease demonstrates that the two high momentum tops in a four top process can be analyzed primarily by using position.

1 Introduction

A Background

All matter in our universe is made of atoms, and all atoms are made of elementary particles. These particles are quarks, leptons, and bosons (Figure 1).

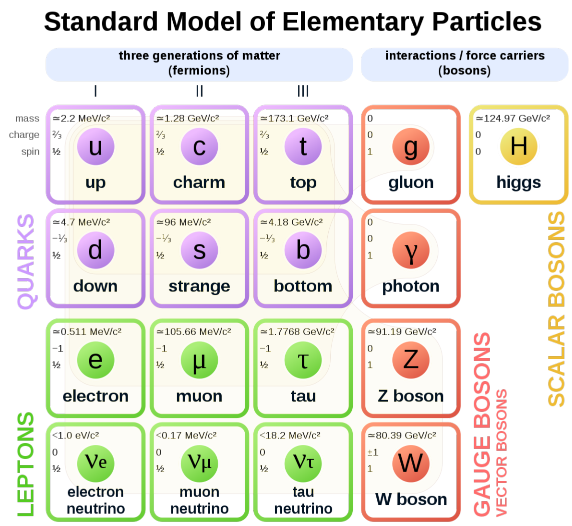

Figure 1: The Standard Model [1]

Up quarks and down quarks combine to form protons and neutrons. There are four other types of quarks also (charm, strange, bottom, and top) but these four quarks are unstable and immediately decay to up or down quarks, so we don't normally experience them. However, through particle accelerators we can create these quarks and study them. The top quark is especially interesting because it has a much greater mass than the other five quarks [2].

The Higgs Field permeates all space and is the field that gives all particles mass. The more a particle interacts with the field, the more mass it has. The Higgs Boson is an excitation of the Higgs Field. It can be thought of as the manifestation of the field as a particle that we have the ability to interact with. Because the top quark is so heavy, it interacts strongly with the Higgs Boson. Why the top quark couples so strongly with the Higgs Boson is unknown, and of great interest to many scientists [3].

B Motivation

Some Beyond the Standard Model (BSM) theories involve new heavy resonances, a heavy particle that decays immediately, that could couple preferentially with top or bottom quarks. If the heavy resonances only couple with the top or bottom quarks, they would have to be produced in a process like the one displayed in Figure 2.

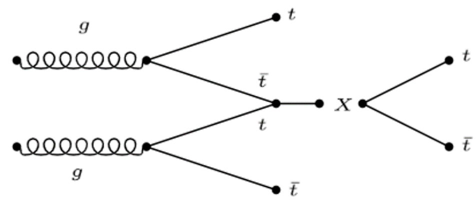

Figure 2: Proposed new process that creates four top quarks in the final state, "X" is the predicted new heavy resonance [4]

This process would create events where four top quarks would be produced in excess of predictions from current theories. If we find new heavy resonances that do have preferred coupling to the top, this could imply that the top quark is composite[1]. Since this process would produce a final state with many top quarks, the kinematics[2] of top quarks needs to be understood so that the four top process can be analyzed.

The process that produces four top quarks produces two top quarks with high momentum[3] and two top quarks with low momentum. Top quarks always decay into a W boson and a bottom quark, regardless of how they are produced. This means that the kinematics of top quarks can be studied without producing the process that we will eventually search for.

2 Methods

A Experimental Set-Up

For this project, the top quarks with high momentum were studied, by looking at a process that creates two top quarks with high momentum. The studied process is shown in Figure 3 where $t\bar{t}$[4] decays into W^+b[5] and $W^-\bar{b}$[6], and then the W^+ and W^- each decay into $q\bar{q}$[7]. The goal of this project was to study how the transverse momentum of the top quark affects the physical distance between the parent top quark and its daughter decays.

Transverse momentum (p_T) shown in Figure 4 is defined as the momentum in the xy plane because it is transverse to the beamline [8], which is defined as the z-axis. So, $p_T = \sqrt{p_x^2 + p_y^2}$. The angle between p_T and the x-axis is defined as ϕ.

The angle between the three-vector momentum and the z-axis is defined as θ. From θ, the pseudo-rapidity is calculated as $\eta = \ln(\tan(\frac{\theta}{2}))$ as seen in Figure 5. An $\eta\phi$ space is created where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Physically, ΔR can be thought of as the angular distance between two particles.

[1] made of multiple parts
[2] study of the movement of body/bodies without taking into account the forces acting upon them
[3] momentum is defined by a particles mass multiplied by it's velocity
[4] $t\bar{t}$ denotes a top quark, anti-top quark pair
[5] W^+ denotes a positively W boson, and b denotes a bottom quark
[6] W^- denotes a negatively charged W boson, and $\bar{b}$ denotes an anti-bottom quark
[7] $q\bar{q}$ denotes any quark, anti-quark pair
[8] the beamline is the trajectory of the beam of particles created by the particle accelerator

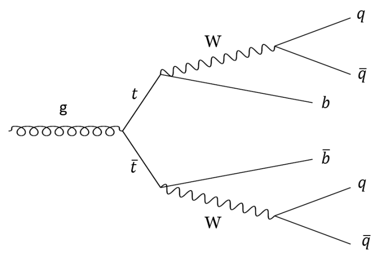

Figure 3: Feynman Diagram of $t\bar{t}$ decay.

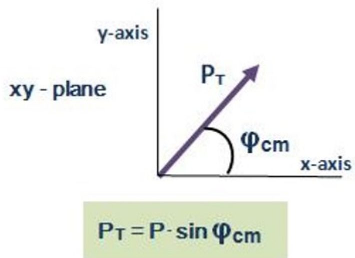

Figure 4: Transverse Momentum [5]

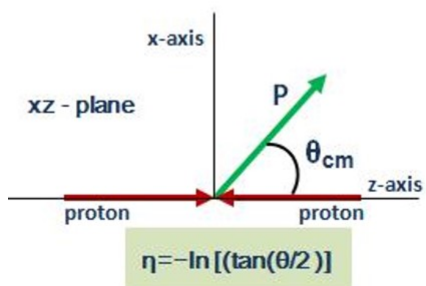

Figure 5: Pseudo-Rapidity [5]

B Data Analysis

A data set of the process in Figure 3 with 100,000 events[9] was produced using MADGRAPH, a Monte Carlo simulation software package. MADGRAPH simulated $p\bar{p} \to t\bar{t}$, $t \to W^+ b$, $\bar{t} \to W^- \bar{b}$, $W^+ \to q\bar{q}$, and $W^- \to q\bar{q}$.

First, I calculated η and ϕ for each bottom quark, W boson, and top quark parent. After pairing each bottom quark and W boson with its respective top quark parent, I calculated $\Delta\eta$ and $\Delta\phi$ for each bottom quark and W boson. $\Delta\eta = \eta_b - \eta_t$ or $\Delta\eta = \eta_W - \eta_t$ where t is the top quark parent to either the bottom quark or the W boson. $\Delta\phi$ was calculated using the ROOT Function, "DeltaPhi", to adjust for the fact that 0 and 2π are the same value. This ROOT function converts the $\Delta\phi$ value to be between $-\pi$ and π.

Using $\Delta\eta$ and $\Delta\phi$, I calculated $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ as seen in Figure 6. This value is essentially the distance between the bottom quark or the W boson and its top quark parent.

[9] decays shown in Figure 3

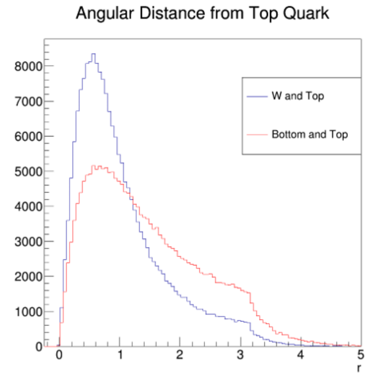

Figure 6: ΔR for the W boson and bottom quarks.

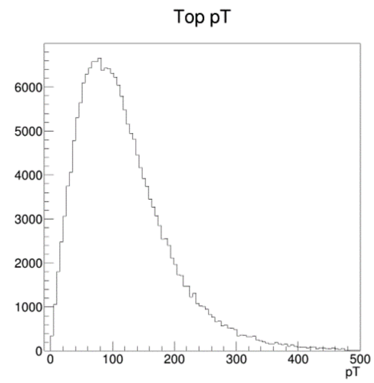

Figure 7: Top quark p_T

Next, I plotted p_T for all of the top quarks (Figure 7). But, I wanted to study how different ranges of top quark p_T effects the ΔR value. So, I separated top quark p_T into $p_T < 100, 100 < p_T < 200, p_T > 200$ and calculated $\Delta\eta, \Delta\phi$, and ΔR for the three ranges of p_T for both each W boson and its top quark parent, and each bottom quark and its top quark parent.

3 Results

As top quark p_T increases, $\Delta\eta$ and $\Delta\phi$ are closer to 0. Also, as top p_T increases, the peak for $\Delta\eta$ and $\Delta\phi$ narrows. I then calculated ΔR for the W boson and the bottom quark with respect to its top quark parent, as shown in Figures 8 and 9.

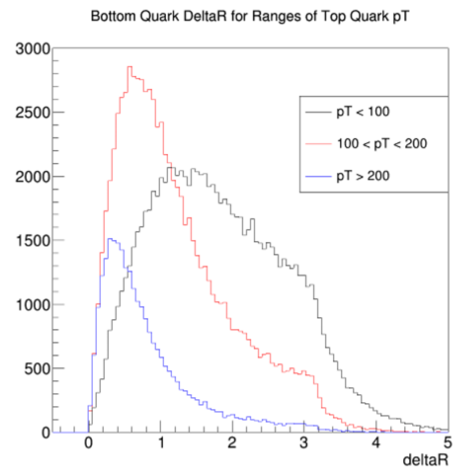

Figure 8: ΔR between bottom quarks and top quark parent for ranges of top quark p_T

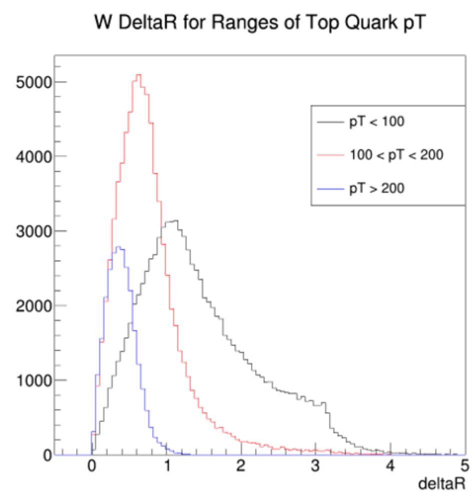

Figure 9: ΔR between W boson and top quark parent for ranges of top quark p_T

4 Discussion

In conclusion, as top quark p_T increases, ΔR for the W boson and the bottom quark decreases. This means that as top quark transverse momentum increases, the distance that between the top quark decay products and its parent top quark decreases. Experimentally, this means that looking for top quarks with high momentum can primarily be done through position tracking since the decays that will be detected are physically close to their parent particle in the detector.

The next steps to this project would be to do the same analysis while simulating the particle decays as jets, which would be more accurate to what the detectors actually measure. This analysis studied the top quarks with high momentum, but the two top quarks with low momentum need to be studied to determine the best way to track their position in the detector. Once these simulations are used to understand how to analyze the high and low momentum top quarks decay, real data from the ATLAS detector will be used to search for the four top decay process as described in Figure 2.

5 Acknowledgements

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