# Potential Observation of Simultaneous Production of 4 Top Quarks in ATLAS Data

Computing for Particle Physics Final Project

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# Introduction

The standard model of particle physics continues to face rigorous testing to determine not only the limits of the theory but also the areas of knowledge which require further investigation. One such area is the top quark, the partner of the bottom quark in the third generation of quarks in the standard model. Its extremely high mass, larger by an order of magnitude than the other quarks and notably heavier than the bosons, has yet to be explained. Beyond the usual TTbar decays which are used to analyze the top quark, there are other events involving the top which draw attention. The top's interactions with the Higgs Boson and Z boson show promise, but the 4 top quark production is the concern of this paper. A significant peak in the dimuon invariant mass around the expected area of the 4 top quark appears in data from ATLAS has been observed, indicating the possibility that candidate events are present in current data sets.

# Data

The ATLAS data contains 100,000 events of momentum and energy information for electrons, muons, and jets as well as the corresponding missing transverse energy. The events were filtered so that only events containing two muons with opposite charges were kept in the data set. The invariant mass was calculated by subtracting the square of the total momentum components from the square of the sum of their energies (Eq. 1)

$$\sqrt{E_{tot}^2 - p_{x,tot}^2 - p_{y,tot}^2 - p_{z,tot}^2} \qquad \text{(Eq. 1)}$$

Then the data was plotted over 6 ranges in order to make the peaks more visible. The ranges are from 0 to 5,000; 5,000 to 15,000; 15,000 to 125,000; 100,000 to 200,000; 200,000 to 400,000; and 400,000 to 1,400,000.[1] The data was plotted using matplotlib histograms, and several notable peaks were present.

# Results

Four peaks were observed in the dimuon invariant mass distributions. The first three indicate agreement with previously discovered particles.

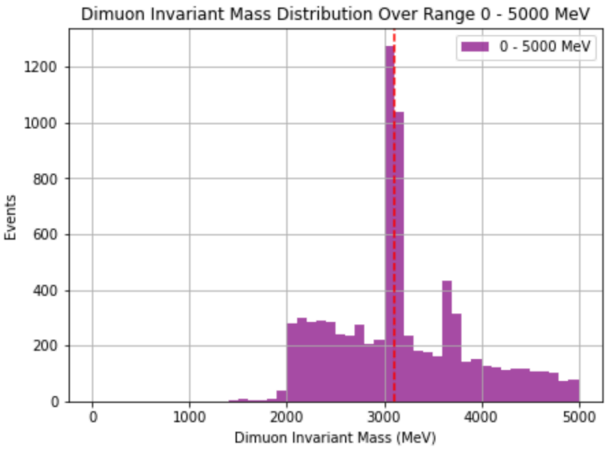



Figure 1: Distribution of dimuon invariant mass over range 0-5,000 MeV with a vertical line at the expected value for the J/Psi meson (3.10 GeV).

Figure 1 shows the spike in the data which agrees with the expected value for the

[1] Since the data is from ATLAS, the data is in MeV, as are the ranges.

J/Psi meson at 3,100 MeV. Also visible is the first excited state of the J/Psi meson at a smaller peak around 3,750 MeV.

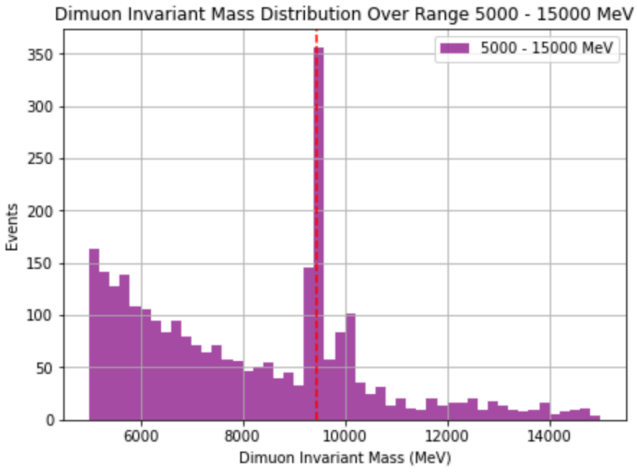



Figure 2: Distribution of dimuon invariant mass over range 5,000-15,000 MeV with a vertical line at the expected value for the Upsilon meson (9.46 GeV).

Figure 2 shows the spike in the data which corresponds to the Upsilon meson at 9,460 MeV as well as the first excited state at around 10,000 MeV.

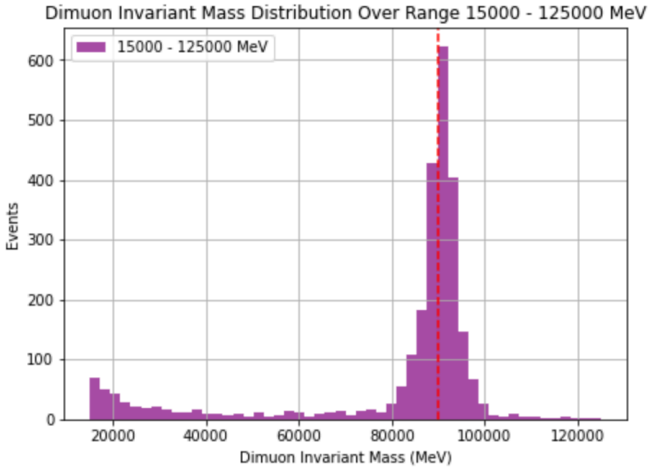



Figure 3: Distribution of dimuon invariant mass over range 15,000-125,000 MeV with a vertical line at the expected value for the Z boson (90 GeV).

Figure 3 shows the peak which agrees with the expected mass of the Z boson at around 90,000 MeV.

The fourth and fifth plots do not contain discernible peaks, but they are included in the index. The plot of interest in this case is the sixth as seen below.

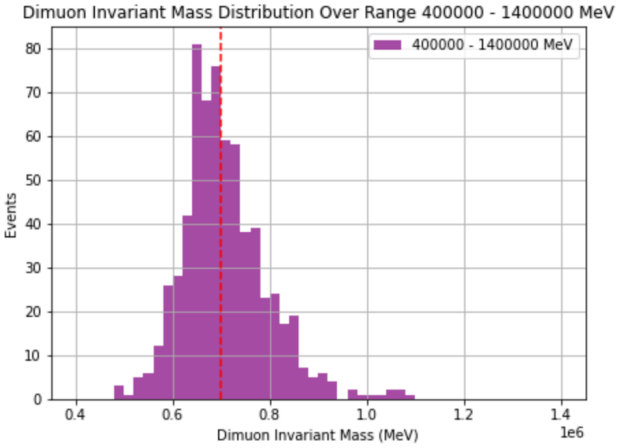



Figure 4: Distribution of dimuon invariant mass over range 400,000-1,400,000 MeV with a vertical line at 700 GeV, the potential mass of the 4 top quark production.

Figure 4 contains a notable peak that is around the area of 700,000 MeV, precisely the anticipated value of the 4 top quark production process. The wide distribution of the peak relative to the others further indicates the short lifespan of the top quark relative to the other particles visible in the data set.[2]

The observed peak matches the results found by the ATLAS collaboration in March 2023, where they claimed to have observed the simultaneous production of four top

[2] The top quark has an extremely short lifespan (5 x 10^-25 s), so short in fact that it cannot hadronize.

quarks at the LHC by looking at dimuon decays like those plotted here.[3]

## Conclusion

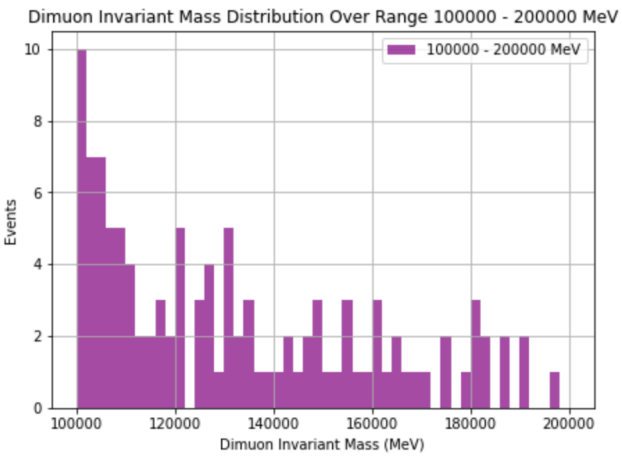
The peaks in the dimuon invariant mass distribution plots strongly indicate the presence of the J/Psi, Upsilon, Z boson, and four top quark production in the data set. The peaks align convincingly with anticipated values for the masses of the particles, leading to the conclusion that these events are in fact present.

It is important to note the significance of the y-axis scales on the histograms. There are thousands of events around the peaks for the J/Psi, Upsilon, and Z boson, but there are only a few hundred around the four top quark production peak. The candidate events for the four top quark production are very rare, and the number of events which survived the cut criteria is quite small in the region above 400 GeV. It is also important to note that the peak around 700 GeV is not present in the data set from CMS which was investigated as a part of this project. The plots for the CMS data can be found with the full set of ATLAS plots in the index.

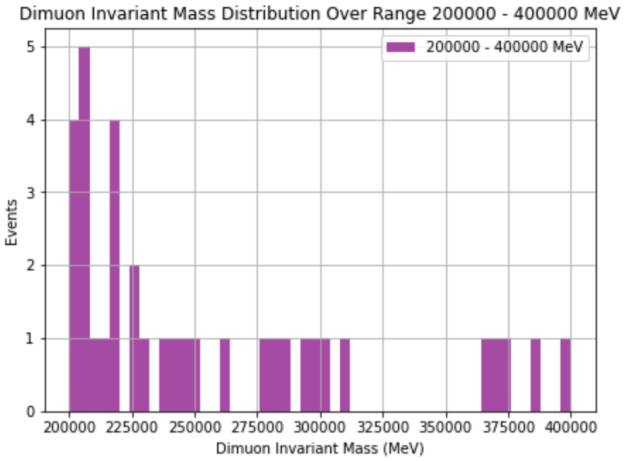
The simultaneous production of four top quarks, and our ability to detect and characterize it, is promising for continued investigations of the top quark in pursuit of a deeper understanding of its mass and its interactions with other massive particles.

[3] Aad, G. et al. 'Observation of four-top-quark production in the multilepton final state with the ATLAS detector,' Eur. Phys. J. C 83 (2023) 496

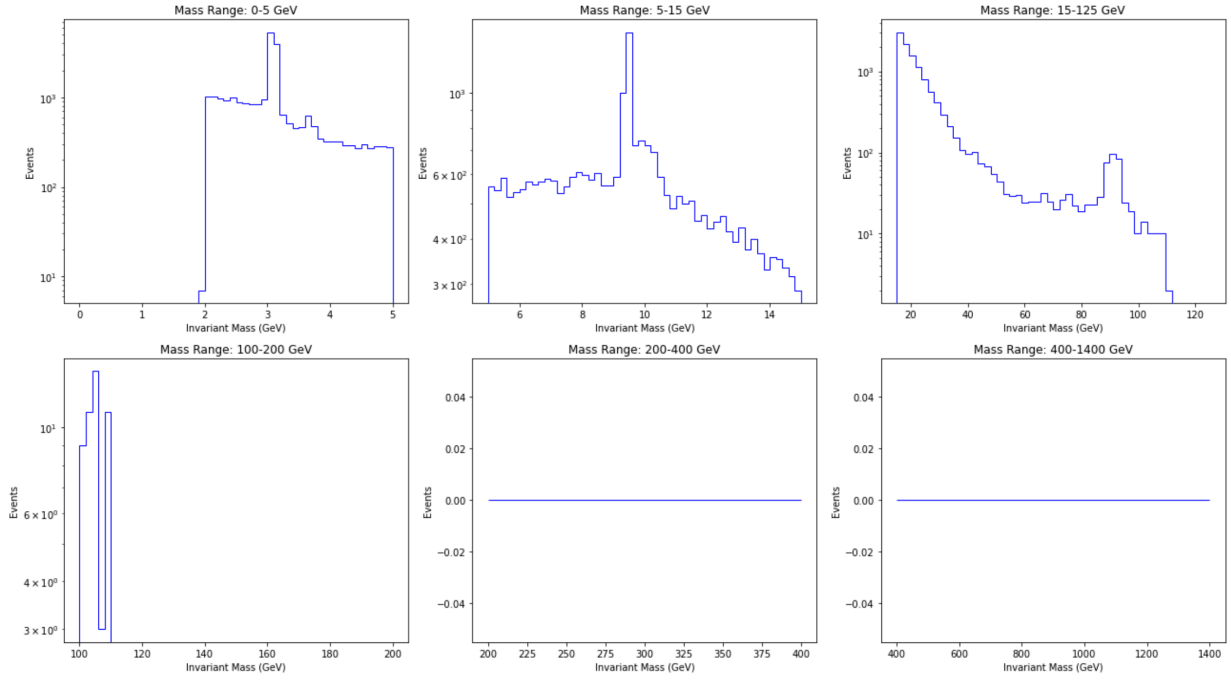
# Index




Index Figure 1: Distribution of dimuon invariant mass over range 100,000-200,000 MeV with no clear definitive peaks.




Index Figure 2: Distribution of dimuon invariant mass over range 200,000-400,000 MeV with no clear definitive peaks.




Index Figure 3: These 6 plots show the dimuon invariant mass distributions for the data provided from CMS. The first three peaks are easily visible like in the ATLAS data (though the excited states are more difficult to make out), but the last peak in the 700 GeV range is not present. In fact, the bins are empty at that high energy level.