Top Quark Properties at LHC

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Abstract

Top quark, the heaviest of quarks, is so heavy that it decays before it can even hadronize, giving us an opportunity to study "bare" quarks. This study thoroughly researches the theory of obtaining the mass of the top quark from the energy distribution of one of its daughter particle, the bottom quark and from the boost distribution of the top quark. It also gives the mathematical proofs behind the observations taken from the graphs of the energy distribution in detail.

Motivation & Importance

The top quark's mass has always been a topic of interest among particle physicists. Even before it was confirmed in 1995, it was realized that certain precision measurements of the electroweak vector boson masses and couplings are very sensitive to the value of the top quark mass making it so much more important to get a really good estimate with great confidence on top quark's mass (173.34 GeV ± 0.27 GeV). We calculate the correlation of the peak of the energy spectrum of the bottom quark with the top quark mass, considering the peak as an observable to determine the top quark mass.

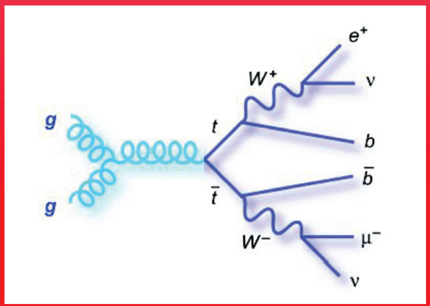

Figure 1 - Top Quark Decay
Credits
http://cylindricalonion.web.cern.ch/sites/cylindricalonion.web.cern.ch/files/users/achintya/ttbar_dilepton.png

Theory

In the rest frame of the top quark, when it decays into the Bottom quark and the W^+ boson, All of the mass of the top quark is in the momentum (equal and opposite) and mass of those two particles. Here we aimed to focus on the momentum (energy) of the bottom quark, find it's distribution in the lab frame coupled with the boost distribution of the top quark, and then finally get a mathematical expression describing it. This can then be used to calculate the mass of the top quark by working in reverse and going from the energy and boost distribution to the mass of the top quark.

Mathematical Proof

- Finding the energy (momentum) of the (assumed to be massless) bottom quark in the rest frame of the Top quark for a single boost value (m_B = Mass of Parent Particle; E_A, P_A = Energy, Momentum of Daughter Particle)

$$(m_B, \vec{0}) = (E_A, \vec{P_A}) + (E_a, \vec{P_a})$$

$$|\vec{P}| = \frac{((m_B^2-(m_a-m_A)^2)(m_B^2-(m_a+m_A)^2))^{1/2}}{2m_B}$$

- Applying the lorentz transform to change this to energy and finding the minimum and maximum for a variable boost distribution - (γ = Lorentz Factor; β = Boost of the Parent Particle E_R = Rest energy of the Parent Particle)

$$E_{min} = \gamma E_R(1-\beta)$$
$$E_{max} = \gamma E_R(1+\beta)$$

- Energy Minimum and Maximum for Massive Bottom Quark -

$$E_{min} = \gamma(E' - \sqrt{(E'^2 - m_b^2)}\beta cos(\theta))$$
$$E_{max} = \gamma(E' + \sqrt{(E'^2 - m_b^2)}\beta cos(\theta))$$

- Features of this distribution -

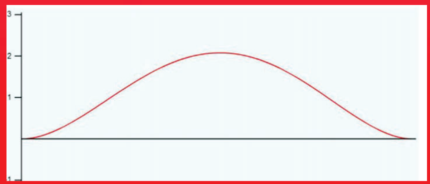

Figure 2 - A gaussian distribution of energy

- Peak lies at E_{BR}

Plot Results

Pythia, an event generator for a large number of physics processes, and Root, an object oriented framework for large scale data analysis, were used to generate top quark events and get the plots of energy distribution of the bottom quarks. Some salient confirmations were that as the energy changed, the peak of the distribution itself didn't change; the distributions were narrow and tall for lower energies and drawn out for higher energies.

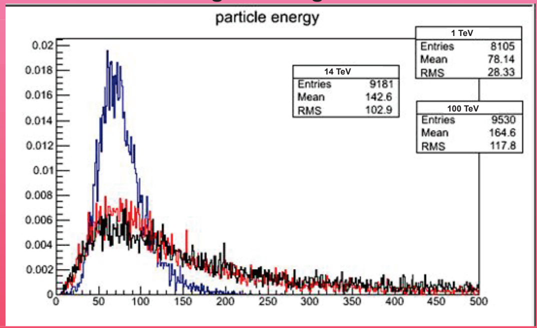

Figure 3 - Plots at different energies (Beam eCM) - Energy is 1 TeV (Blue) ; en is 14 TeV (Red); ener is 100 TeV (Black)

Conclusions & Future

We proved the result that the maximum of energy distribution is the same regardless of the boost of the parent particle. This was verified using simulations for top quark decaying into bottom quark.
In the future this could be applied to heavier particles and also extended to studies beyond the standard model.

Acknowledgements

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Agashe, Kaustubh, Roberto Franceschini, and Doojin Kim. "Simple "invariance" of two-body decay kinematics." Physical Review D 88.5 (2013): 057701.

Testing the Extended Randall-Sundrum Model using Same-Sign Dilepton Channels

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Abstract

This study focuses on studying certain same-sign dilepton channel processes that could provide evidence for a higher dimensional universe as proposed by the extended Randall-Sundrum model. There are several processes and channels that provide evidence for this 5-dimensional behavior, but we focused on one specific channel involving a Kaluza-Klein W boson that decays into a Radion and a SM W boson, eventually resulting in a di-lepton and di-jet final state. To carry out our study we used tools such as MADGRAPH, Python, ROOT, and the UMD T3 Computing Cluster.

Randall-Sundrum Model

The Randall-Sundrum (RS) model is a physical model that postulates our universe as a five-dimensional expanse, with our observable universe being a four-dimensional cross-section, or "brane", of the five-dimensional "bulk". In the RS model, there are two branes (IR or TeV and UV or Planck brane). Fields have characteristic wave functions in the bulk. Gravity is localized on the Planck brane while the Higgs field is localized at TeV brane. Other SM fields like gauge fields are flat along the extra dimension and light fermions are peaked at the Planck brane. The RS model uses this to attempt to resolve the "hierarchy problem." The overlap of the 5-D profile of each particle with the Higgs at the TeV brane determines a particle's mass. The extended RS model has three branes, with different fields propagating in different bulks (shown in figure below). The extended region contains SM electroweak gauge bosons as well as the radion, a spin-0 particle looked at in this study, which corresponds to the fluctuation in size of the extra dimension.

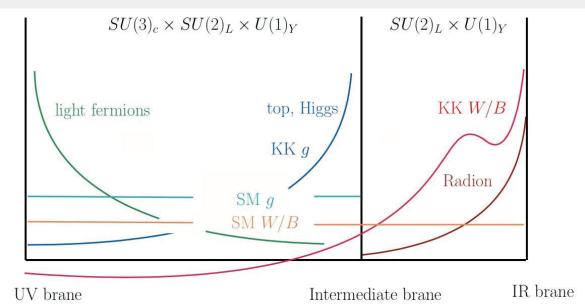

Figure 1. Diagram of the Extended RS Model [2]

Methodology

Our analysis involved running simulated processes using the physics of the extended RS model to see if we could find evidence of new physics when we compared our signal to various SM backgrounds. Using MADGRAPH as our simulator, we imported a new model into that exposed MADGRAPH to certain new particles and couplings postulated by the extended RS model. We then used Delphes for our detector simulation and Pythia to take care of parton distribution and shower simulation. Cuts were used to increase the statistical significance of our signal process against SM backgrounds (Figure 2).

1. Proton-proton collision forming Kaluza-Klein W boson (signal)
2. Proton-proton collision forming 3 SM W bosons (bk)
3. Proton-proton collision forming 2 SM W bosons and two jets (bk)

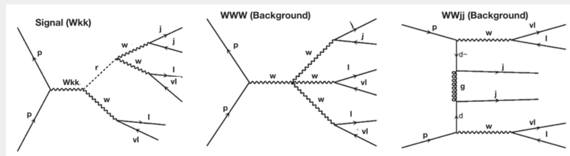

Figure 2. Representative Feynman diagrams for each process

Results

10^4 events were simulated, for the signal process and for each background process. Preselection cuts were applied for events with values for kinematic variables within certain constraints. The preselection cuts applied can be found in the table below (left). During analysis, further cuts were applied for the purpose of limiting the events to a range of kinematic variables in which the signal process is significantly distinct from the background processes, in the simulated events. The cuts applied during analysis can be found in the table below (right), with the associated cross sections and numbers of real events, using luminosity of 300 fb^{-1}.

Preselection Cuts
$\eta_j < 3$
$\eta_\ell < 2.5$
$\Delta R_{\ell\ell} > 0.4$
$\Delta R_{j\ell} > 0.4$
$p_{T_j} \geq 20$ GeV
$p_{T_\ell} \geq 10$ GeV

Table 1: Preselection cuts

Cut Flow	Cross-section (fb)			Real Events		
	S	B_1	B_2	S	B_1	B_2
1. Preselection Cuts	0.0364	1.10	3.54	10.9	329	$1.06 * 10^3$
2. $MET > 175$ GeV	0.0299	0.0597	0.397	8.97	17.9	119
3. $M_{\ell\ell} > 175$ GeV	0.0276	0.0235	0.134	8.28	7.05	40.1
4. $p_{T_{\ell 1}} > 200$ GeV	0.0253	0.0111	0.0382	7.60	3.32	11.5

Table 2: Cut flow (S refers to the signal process. B_1 refers to the $p\,p > W^\pm W^\pm W^\mp$ background process. B_2 refers to the $p\,p > W^\pm W^\pm j\,j$ background process.)

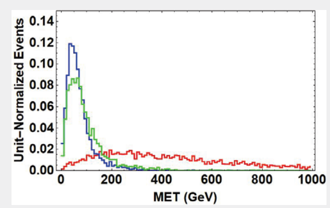

Figure 3. MET for events after pre-selection cuts

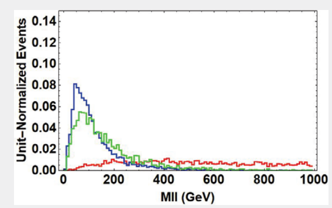

Figure 4. Invariant mass of lepton pair for events after pre-selection cuts

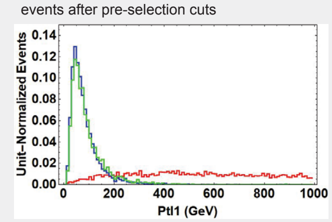

Figure 5. Lesser of the two lepton transverse momenta for events after pre-selection cuts
Key | Signal (red), WWW (blue), WWjj (green)

Conclusions

The final significance value for the cuts performed on the 10,000 simulated events was approximately 1.61. Significance was calculated using $S/\sqrt{S+B}$, where S and B are real signal and background events, respectively. With a projected luminosity of 3000 fb^{-1}, this would result in a significance of approximately 5.08. This would be high enough significance to indicate that this channel would be potentially useful in identifying evidence of physics not accounted for by the standard model. However, luminosity of 3000 fb^{-1} is not currently possible, and is only a projection of hypothetical future development. Given the 300 fb^{-1} luminosity, the significance is not high enough to suggest that same-sign dilepton channels could be potentially used, with the given cuts, to indicate evidence of new physics, although it is perhaps high enough to merit further examination.

References

1) L. Randall and R. Sundrum, Physical Review Letters (1999)
2) K. Agashe, P. Du, S. Hong, and R. Sundrum, Journal of High Energy Physics (2017)
3) K. Agashe, J.H. Collins, P. Du, S. Hong, D. Kim, and R.K. Mishra, Physical Review (2019)