

Kinematic Reconstruction of the Charged Higgs Boson Mass in the $H^+ \rightarrow t\bar{b}$ process using a Likelihood Technique

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Abstract

An extension of the Standard Model of particle physics is an introduction of two Higgs doublets to break electroweak symmetry instead of a single Higgs boson. This results to a couple of Higgs bosons, which includes a charged scalar, $H^\pm$. The H^+ is produced as a mediator in a scattering process of a top quark and a bottom quark coming from two gluon. This CERN Summer Student project report studies how to reconstruct the mass of H^+ using a novel statistical method based on weighting every combination of the final state products which then corresponds to a weighted average mass per event. Histograms on the invariant mass of the H^+ are produced for simulated datasets with different H^+ truth mass.

Keywords: **12.60.Fr** Extensions of electroweak Higgs sector, **14.80.Fd** Other charged Higgs bosons

1 Introduction

The objective of this report is to detail the physics analysis of a Beyond Standard Model event process. An extension of the Higgs sector - the Two-Higgs Doublet Model - introduces two doublets that cause spontaneous symmetry breaking of the electroweak unification, attributed in the Standard Model to a primary scalar neutral Higgs boson [1]. Coming in either a positively charged or negatively charged one, this summer student project focuses on the production of the positively charged Higgs particle, H^+ .

The new method along with the signal process hypotheses is used on a number of datasets which includes simulated events by event generators. The motivation of searching this particle and studying its properties like its mass is the fact that this model is usually used in many Supersymmetry Models of the Standard Model, this prompts a search for "new physics", extending what is known from the Standard Model of particle physics.

The report is based mainly on utilizing a new technique for event reconstruction, specifically the mass reconstruction of a specific particle that decays to a set of lighter particles. This technique widely uses likelihood probability variables such as the ones also used for the discriminant, that discriminates between signal processes and background processes [2, 3].

2 Two-Higgs Doublet Model

In this section, the details of the Two-Higgs Doublet Model will be briefly reviewed which are taken from extant literature [1]. The Two-Higgs Doublet Model (2HDM) was proposed to add a particular feature in supersymmetry. Since a single Higgs doublet cannot give mass simultaneously to quarks of different charges and chiralities since these multiplets (in supersymmetry) have their field complex conjugates of the opposite chirality, scalar fields in supersymmetry theories need another Higgs doublet to cancel anomalies between spin-1/2 and scalar multiplets. This requires, for example, the MSSM or the Minimal Supersymmetry Model to have two Higgs doublets. Aside this, there are many other motivations for the extension of the Higgs sector, this includes generating the baryon asymmetry of the universe by an existence of additional sources of CP violation.

In recent studies in 2HDM phenomenology, it is assumed that CP (charge and parity) is conserved in the Higgs sector while considering all possible quadratic coefficient terms for the potential. Introducing two doublets, Φ_1 and Φ_2 with hypercharge $Y = 1$ (for $\rho = 1$), the most general scalar potential is:

$$V(\Phi_a) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{21}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \quad (1)$$

$$+ \frac{\lambda_3}{2} (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \frac{\lambda_4}{2} (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} ((\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2) \quad (2)$$

The Higgs doublets has the vacuum expectation values from the minimization of the potential as:

$$\langle \Phi_a \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_a}{2} \end{pmatrix} \quad (3)$$

with $a = 1, 2$. There are a total of 8 fields from 2 complex scalar SU(2) doublets:

$$\Phi_a = \begin{pmatrix} \phi_a \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix} \quad (4)$$

with v_a as the vacuum expectation value and after spontaneous symmetry breaking, the remaining fields are the $W^\pm$, Z^0 gauge bosons and 5 physical scalar (Higgs) bosons. Among the numerous Higgs bosons, we have a charged one ($\pm$), two neutral ones and a pseudoscalar one. This report focuses on the charged Higgs boson with the reconstruction of its mass which is a free parameter proposed to have a Lagrangian mass term equal to: $m_\pm^2 = [m_{12}^2/(v_1 v_2) - \lambda_4 - \lambda_5](v_1^2 + v_2^2)$.

Lastly we show how the charged Higgs boson couples to fermions by a Yukawa coupling terms in the Lagrangian:

$$\mathcal{L}_{H^\pm} = -\phi^\pm \left(\frac{\sqrt{2}V_{ud}}{v} \bar{u}(m_u X P_L + m_d Y P_R)d + \frac{\sqrt{2}m_l}{v} Z \bar{\nu}_L l_R \right) + h.c \quad (5)$$

where u, d are up-type and down-type quark fields, m_u, m_d are the masses of the up-type and down-type quarks, V_{ud} is the appropriate CKM matrix for quark mixing, ν_L, l_R is the left-handed neutrino and the right-handed lepton coupling, and m_l is the lepton mass respectively. P_L and P_R are just projection operators for chirality while the constants X, Y and Z are model dependent variables related to the phenomenological rotation angle $\beta = \tan^{-1}(v_2/v_1)$ which diagonalizes the mass-squared matrices of the charged scalars and pseudoscalars which determines the interaction of the various Higgs fields with vector bosons and fermion fields.

After having discussed a bit about the background of the charged Higgs boson, its origin and motivation, the report now focuses on specific experimental nature and physics data analysis on searching the charged Higgs boson in the next sections.

3 Event Diagram

Typically, a proton-proton collision in a hadron collider produces a bunch of gluons. For this summer student project the production of $H^\pm$ bosons in association with a top and a bottom quark and the decay into a top and a bottom quark are considered. The production and decay of $H^\pm$ is shown in the tree-level Feynman diagram below (Figure 1).

Furthermore, the top quarks associated in the scattering event decays into a bottom quark and a W boson, its most probable branching fraction. The resulting W boson decays either hadronically, to a pair of light quark jets with masses less than the top quark, or leptonically, - either an electron or a muon - and a lepton neutrino.

The signal process (Figure 1), is completely described by

$$gg \rightarrow \bar{t}bH^+ \rightarrow t_{l\nu_l b_{lep}} t_{b_{had1} q_1 q_2} b_{had2} b_{other} \quad (6)$$

with a probability that the top quark either decays hadronically or leptonically as described in the previous section. The particles involved in the signal process is named in Figure 1 as follows, (where we can ignore the fact that some are antiparticles for the meantime) t_{lep} as the top quark that decays leptonically, W_{lep} and b_{lep} for the leptonic W boson and bottom quark that decays from t_{lep} , while for the top quark and the bottom quark from the hadronic decay is named t_{had} and b_{had} with W_{had} decaying into q_1 and q_2 .

However, there also exists another process that can result to the same final products with the signal process. This background process, described by a Feynman diagram in Figure 2, is the production of a $t\bar{t}$ pair shown in association with two bottom quarks. This also starts off with two gluons decaying into top quarks instead of the other one decaying into a bottom quark pair. The count of bottom quarks can be more than in the signal process since the gluon can interact with itself and split to other gluons which can decay into bottom quarks. As with the signal process, the $t\bar{t}$ process can also decay hadronically or leptonically with specific probability. All other background events having the same final products are of subdominant nature so that they can be ignored [4, 5].

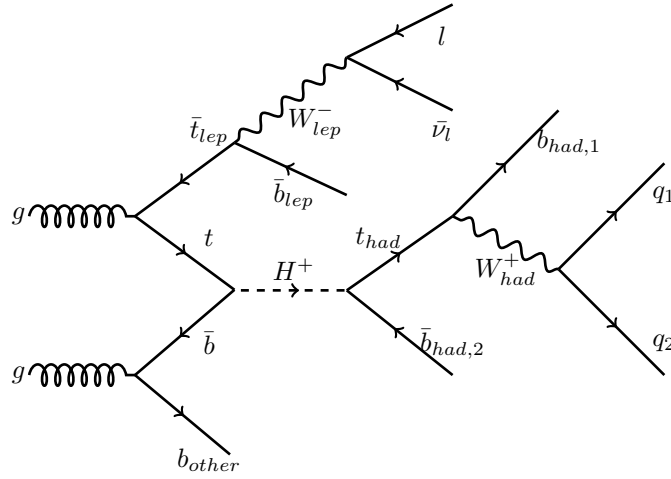


Figure 1: Signal process: The production of a virtual H^+ from a scattering of a top quark and an anti-bottom quark from a gluon decay to top-anti-top and bottom-anti-bottom pair. The hadronic decay of the top quark and the leptonic decay of the anti-top quark is shown as a proxy for all possible top quark decays.

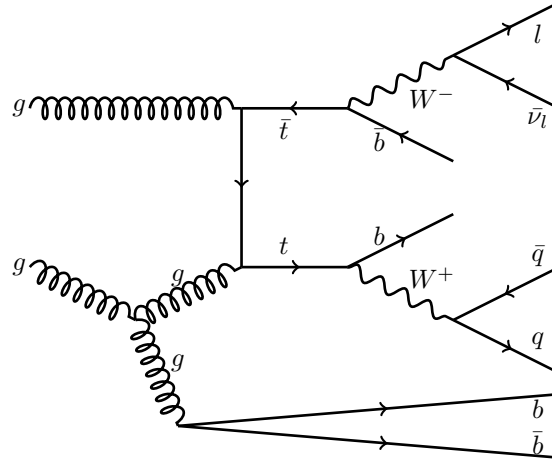


Figure 2: Background Process: The production of a virtual $t-\bar{t}$ pair from two gluons with the top quarks decaying into the same products as the signal process. Additional bottom quarks can be obtained from gluon splitting.

4 Physics Analysis: Event Categorization

Given a dataset of collision events, we can effectively categorize and select the ones having what we want - the final products - using a selecting algorithm. Selecting this events to have our particular products, one can discriminate the events being associated to our signal and background process, so that the analysis may be constrained only to those events that possibly have the H^+ for the signal process and $t\bar{t}$ for the background process.

The following cuts are made to categorize the event datasets: (1) For a leptonic top decay, a single lepton - either a muon or a electron, (2) for a hadronic top decay, 5/6 or more light quark jets, and lastly, (3) 3/4 or more of these are tagged as bottom quark jets.

The effect of the bottom quark cut from all of the quark jets from an event, for example, is shown below (Figure 3 and 4) for 18k events:

Figure 3 shows a 2D plot with comparing number of quark jets and the number of bottom quark jets with the number of events described with the color (violet being the lowest and red being the highest). Without the cuts, most events have at least 4 jets with none of them having bottom quarks. However the most probable combination without the cuts are those having 3 bottom quark jets among 6 quark jets, which in hindsight, still is within the cut. After applying the cut, the number of events are reduced to almost 17% of the original number of events, with the most probable combination of quarks and bottom quarks are 6:4 and still having events with quark jets as many 10 and 6 bottom quark jets.

Although with neutrinos coming along the leptons in leptonic decays, one cannot measure these in detectors. However, its presence can be inferred from missing transverse energy (E_T^{miss}). Assuming that

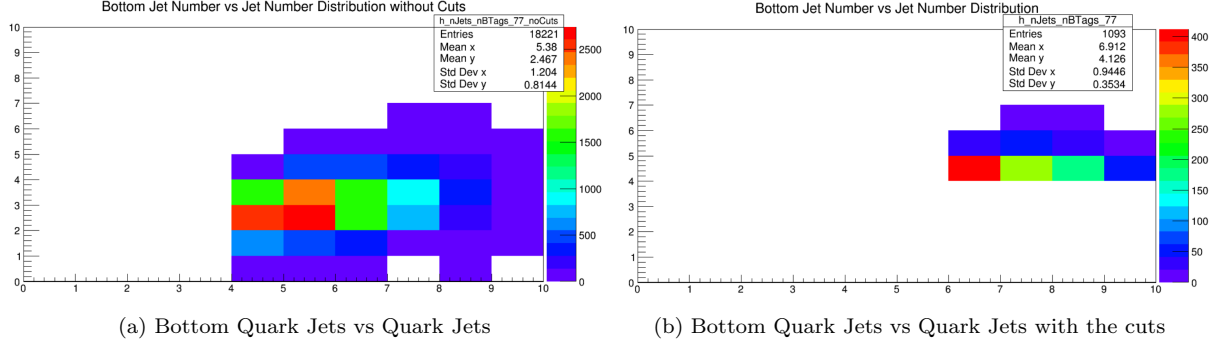


Figure 3: An example of applying the cuts within the events for categorization. Cutting to 4 bottom quark jets in 6 quark jets, the number of events passing the cuts are reduced greatly (From 18×10^3 to 1×10^4), with most of the events having the lowest number of jets allowed in the cuts.

the neutrino momentum in the x - and y -coordinate is equal to the missing transverse energy along those directions and its mass to be 0, we can completely characterize the 4-momentum of the neutrino by considering the requirement:

$$(p_\nu^\mu + p_l^\mu)^2 = (M_W)^2 \quad (7)$$

wherein the sum of the four-momenta of the neutrino and the lepton must be equal to the mass of the mother W boson. In this equation, we have the unknown p_z of the neutrino. Solving this second-order equation, we can obtain either two or one solution, with the case of the no solution being scaled to have exactly single solution.

5 Physics Analysis: Charged Higgs (H^+) Discriminant

To isolate the signal process from the background, a statistical variable called a discriminant D_{H^+} is calculated. This variable returns a number from 0 to 1, depending on how similar the event is to an average H^+ event or how likely an event process is associated to H^+ , with 1 being the closest. This is calculated as follows:

$$D_{H^+} = \frac{\sum_{N_p} P_{sig}}{\sum_{N_p} (P_{sig} + P_{bkg})}. \quad (8)$$

The signal/background probability, $P_{sig/bkg}$, uses templates generated from Monte Carlo event generators (Powheg+Pythia8) having specific probabilities for either signal or background process. These probabilities are summed over all the parton combinations, N_p , that are possible. Given a number of partons in the final state, they are matched into 5 places, 5 light quark jets with 3 of them into bottom quark jets. For 5 partons - $5! = 120$ combinations, 6 partons - $6! = 720$ combinations, 7 partons - $7 \cdot 6 \cdot 5 \cdot 4 \cdot 3 = 2520$ combinations are obtained.

The probability of either signal or background process is calculated by from the kinematic probability, P^{kin} , or the probability of an event to have a certain mass (mass probability, $P(M)$) of a specific particle/s, and the quark jet weight tagging probability, P^{btag} , or the tagging weight of a specific quark jet to be a bottom quark jet instead of other quark jets which is calculated from multivariate analysis. This is calculated as follows: $P_{sig/bkg} = \sum_{N_p} P^{kin} P^{btag}$ [2]. The total P^{kin} for the signal and background process is calculated as follows:

$$P^{kin} = P(M_{t_{lep} \rightarrow b_{lep} l \nu}) P(M_{W_{had} \rightarrow q_1 q_2}) P(X_{H^+}) P(X_{t_{had}}) \quad (9)$$

The variable $P(M_{t_{lep} \rightarrow b_{lep} l \nu})$ is the mass probability of the leptonic top t_{lep} , or the mass of the daughter products - bottom quark jet, lepton and a neutrino ($b_{lep} l \nu$), of the leptonic top decay. The variable $P(M_{W_{had} \rightarrow q_1 q_2})$ is the mass probability of the W boson from the hadronic top decay, or the mass of the daughter products - two light quark jets (q_1 and q_2) for the probability that the hadronic W decay either inside the H^+ decay chain or not. The variable $P(X_{H^+})$ is defined in the following:

$$X_{H^+} = \begin{cases} M_{H \rightarrow b_{h1} b_{h2} q_1 q_2} - M_{t_{had} \rightarrow b_{h1} q_1 q_2} & , \text{ hadronic decay chain} \\ M_{H \rightarrow b_{l1} b_{l2} l \nu_l} - M_{t_{lep} \rightarrow b_{l1} l \nu_l} & , \text{ leptonic decay chain} \end{cases} \quad (10)$$

wherein for a hadronic decay of the top quark from the H^+ , X_{H^+} is the difference of the mass probabilities of the hadronic top decay products ($b_{h1} q_1 q_2$) and the mass of the H^+ hadronic decay chain products ($b_{h1} b_{h2} q_1 q_2$) to reduce the correlation between the former and the latter to have a good approximation on the factorization of the kinematic probabilities. Same goes for a leptonic decay of the top quark from the H^+ , where X_{H^+} is the difference of the mass probabilities of the leptonic top decay products ($b_{l1} b_{l2} l \nu_l$) and the mass of the H^+ leptonic decay chain products ($b_{l1} l \nu_l$). Lastly the variable $P(X_t)$ is the following probability:

$$X_t = M_{t_{had} \rightarrow b_{h1} q_1 q_2} - M_{W_{had} \rightarrow q_1 q_2} \quad (11)$$

wherein X_t is the difference between the masses of the hadronic top decay products ($b_{h1} q_1 q_2$) and the hadronic W boson decay products (q_1 and q_2) to, similarly in X_{H^+} , reduce the correlation between the mass probabilities of the two.

In summary, the kinematic probability, P^{kin} , of a given event is just the product of the mass probabilities of four significant terms taking part in the $H^+ \rightarrow t \bar{b}$ process: the mass probability of the leptonic top decay products, the hadronic W boson decay products boson and the partial correlation of the hadronic top decay products and the H^+ decay products for either a leptonic or hadronic decay chain.

Lastly, to calculate the signal/background probability, the quark jet weight tagging probability which is just the product of the five parton-jet assignment denoted in the signal and the background process as:

$$P_{sig}^{bttag} = P_b(j_1) P_b(j_2) P_b(j_3) P_l(j_4) P_l(j_5) \quad (12)$$

$$P_{bkg}^{bttag} = P_b(j_1) P_b(j_2) P_l(j_3) P_l(j_4) P_l(j_5) \quad (13)$$

wherein j_i are the 5 parton-jet slots with the 3 of them being tagged as a bottom-quark jet and two as light quark jets, while $P_f(j_i)$ is the probability that the particular jet j_i , using a bottom quark jet tagging algorithm, has a quark jet tagging weight value as a particular flavor with b = bottom quark and l = light quark jet. This tagging algorithm uses multivariate analysis with different efficiencies [2].

Showing an example of the distribution of the charged Higgs discriminant values for a given 18k events, Figure 4 shows a histogram with values ranging from 0 to 1. With the cuts applied, we have the most probable discriminant value in the 0.6 range. The values having less than 0.5 value is roughly the background process and those higher than 0.5 is roughly close to the signal process. Judging from the shape of the histogram, the peak is skewed more to the left, which means that most of the events are associated to H^+ giving a coarse-grained separation between the signal events and the background events.

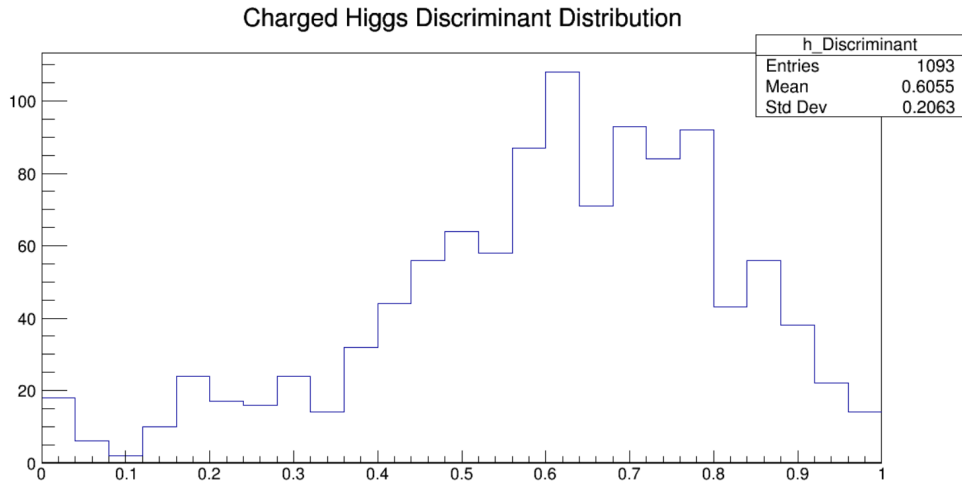


Figure 4: Number of Events versus Calculated Discriminant Value

Furthermore the events has probabilities into three cases: (1) APM or all partons matched, wherein every quark jet are assigned to a specific parton either being a light quark jet or a bottom quark jet, (2) MJ or missing jet, wherein a jet is not tagged correctly, and lastly (3) APM+MJ, wherein the event has certain weights on being either APM and an MJ.

6 Analysis Strategy: Weighted Averages per Parton Combination

The strategy for the physics analysis comes from compensating the large number of combinations possible for parton-jet assignment in each event with the least bias for the mass reconstruction of the signal and the background process.

The mass reconstruction is done by first isolating a single event and calculating the kinematic probability as a corresponding weight for the mass of the H^+ per possible combination. This is filled into a distribution of the weighted mass over all the combinations in a single event with the weighted average as the mass for that event instead of a resonance peak. This is then collected for a number of events to form a distribution of weighted average mass per event. From this distribution, the resonance peak will be the mass of the H^+ for the signal process and $t\bar{t}$ for the background. The separation between the signal process and the background process is qualitatively observed and different truth masses from the templates are used for further recalibration of the used weighted average technique and generation of the event simulation templates.

The weights (w_i) per given combination are calculated as with the kinematic probability, with the difference of the exclusion of the partial correlation for the H^+ mass probability.

$$P_{sig,w/o H^+}^{kin} = w_i = P(M_{t_{lep} \rightarrow b_{lep} l \nu}) P(M_{W_{had} \rightarrow q_1 q_2}) P(X_t) \times P_{sig}^{bttag} \quad (14)$$

This is done to avoid statistical bias in the reconstruction of the mass of the H^+ since having the mass probability of the H^+ inside the weights would shift the distribution peak to the truth mass from the templates which would defeat the purpose of the reconstruction itself. This is done in the APM, MJ and APM+MJ case.

Given a single example event passing the cuts (having 8 jets and 4 bottom jets), the weights w_i per possible combination within the parton-jet assignment are filled into a semi-log histogram plot (Figure) along with the calculated H^+ mass (300 GeV truth mass from the simulations) from the particles respective of either a H^+ hadronic decay chain or leptonic decay chain (accounting either 1 or 2 solutions for the neutrino momenta). In this histogram, the important parameter is the weighted average mass, not the resonance peak. This will be the H^+ mass for this single event.

Comparing the three histograms, it can be seen here that indeed, the resonance peak should not be the one to be noted but the weighted average mass to account for the kinematic probability as the weights in every possible combination given an event. This is seen for example in Figure 5a we have two peaks which if taken lightly could be interpreted as a particle occurring in the masses 250 GeV and 650 GeV, but when the weight is accounted for to calculate a weighted average value, the mass is equal to 394 GeV. Comparing the three cases (APM, MJ and APM+M), the values for the mean are somewhat close to each other, along the range of 300 GeV, with the APM and the APM+MJ case being closest to one another.

7 Mass Reconstruction: Charged Higgs Mass

In this last section, we present the reconstructed H^+ invariant mass by plotting the weighted average mass per event into a large number of events. Having 18k events, and a truth mass of 300 GeV, the mass reconstruction plot is shown in Figure 6 comparing APM, MJ and APM+MJ case. We compare first the histograms in Figure 6 for a 300 GeV truth mass in the three cases (APM, MJ and APM+MJ case). Comparing the mean values, the three histograms have fairly close to one another. Not much difference is seen in terms of the shape. But one thing to be noted here is the value of the mean and the position of the peak value of the distribution. Since the data used here is from a 300 GeV H^+ truth mass, so it is expected that the peak is around the 300 GeV range. However, this is not the case in the reconstruction plot, since we see from the histograms that the peak is around 150 GeV range and the mean along the 200 GeV range, which is nowhere near the 300 GeV range. We investigate this further by trying different truth masses, more bins for the histograms and more events to plot.

Comparing different truth masses, 200 GeV, 300 GeV, 400 GeV and 1000 GeV, the normalized overlaid reconstruction plots are shown in Figure 7 with increased number of histogram bins and events used (50×10^3). Shown in different colors to distinguish the four truth masses used, we see in Figure 7 the 200 GeV (blue), 300 GeV (red), 400 GeV (green) and 1000 GeV (black) truth mass. Comparing the shape, we

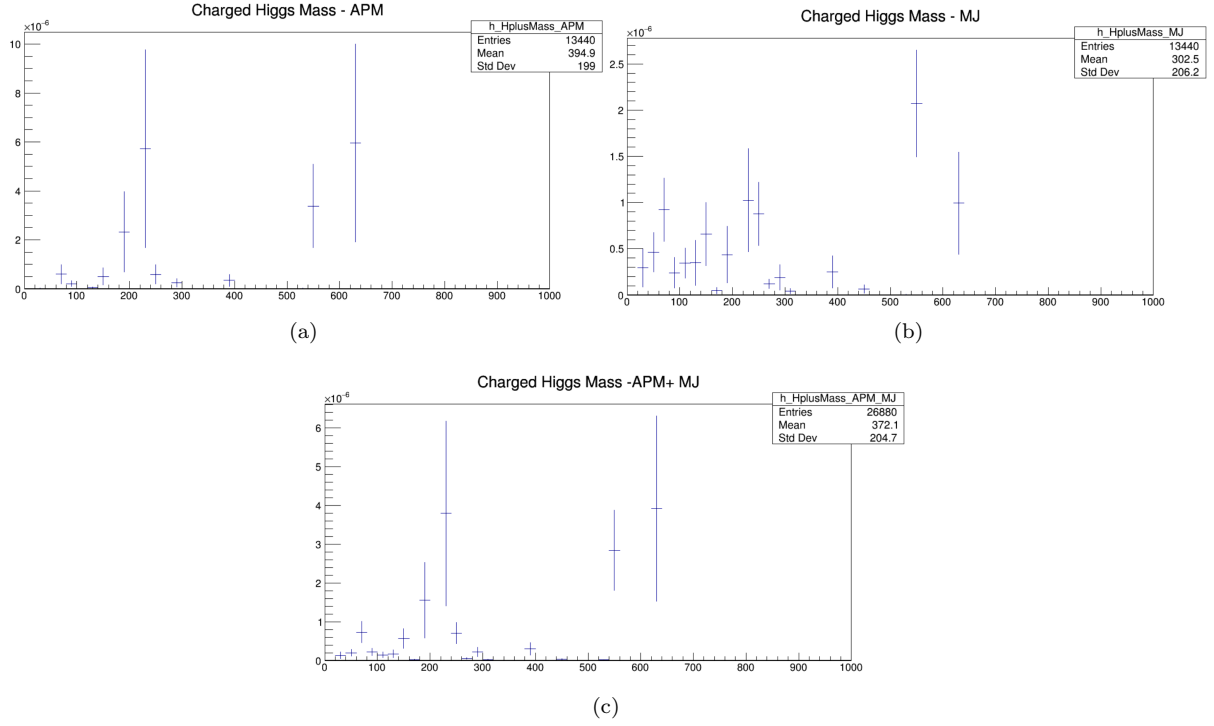


Figure 5: Weighted H^+ mass per single combination of parton-jet assignment (Number of combinations vs mass in GeV) in the (a) APM case, (b) MJ case and (c) APM+MJ case. This is a single example event having 8 quark jets as 4 bottom quark jets. The weighted average mass or the mean will be the recorded H^+ mass for this particular event.

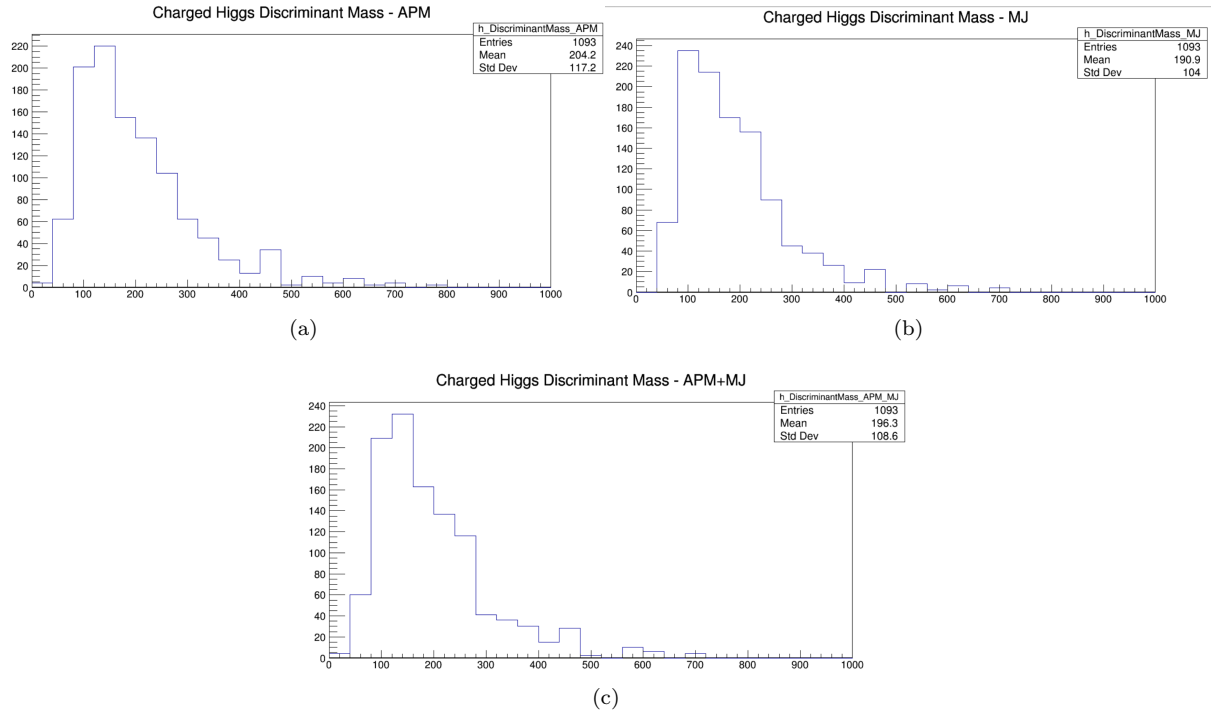


Figure 6: Weighted average H^+ mass per single event in the (a) APM case, (b) MJ case and (c) APM+MJ case. These events are taken from simulations with a truth mass of 300 GeV. The resonance peak supposedly will be the reconstructed mass of the H^+ corresponding to the truth mass.

see immediately that the histograms move accordingly to the right as we increase the mass. Comparing

Charged Higgs Discriminant Mass - APM+MJ

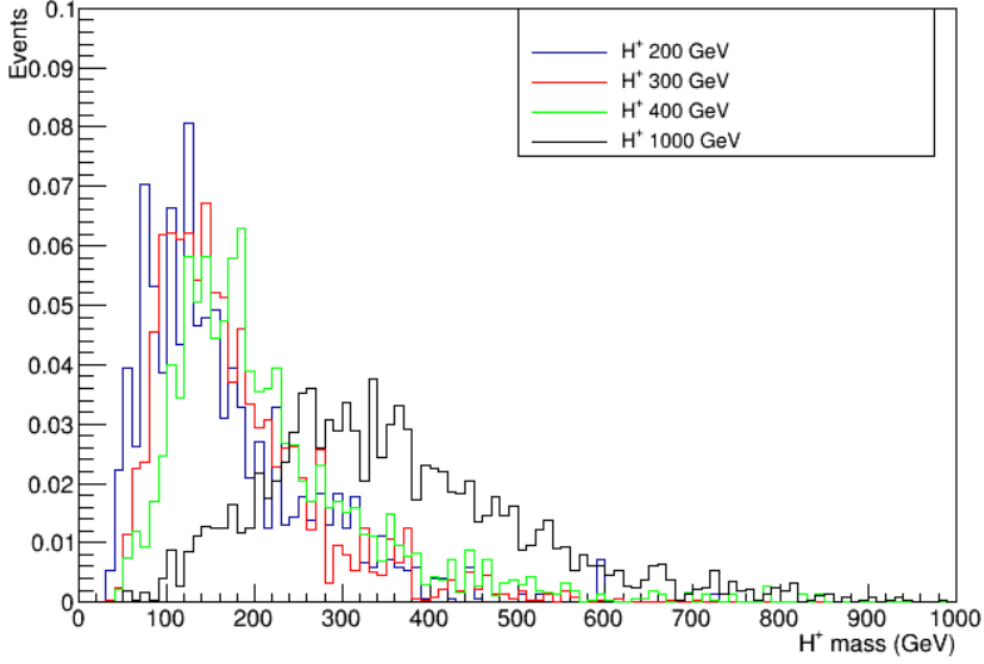


Figure 7: Number of Events versus H^+ invariant mass. The following calculated mean values per histogram - (200 GeV): 167.826, (300 GeV): 178.225, (400 GeV): 217.355, (1000 GeV): 359.692

their heights, this decreases as we increase the truth mass, having the 1000 GeV (black) histogram being flatter than any of the other histograms. Since these are normalized, this comparisons can be assumed safely. Comparing the mean values for the varying truth masses, we have an increasing values for the means in the four histograms. However, this increases slowly as we had the 1000 GeV histogram mean only at 360 GeV. A lower peak effectively means that there is a large chance that other quark jets are used for the combinations such as the one not coming from the H^+ therefore having a lower average transverse momentum thus having a lower mass on average.

Lastly, we compare the different truth masses with the background process ($t\bar{t}$) to observe signal-to-background separation/discrimination, shown in Figure 8. Comparing the signal and the background process, we see that for the first three histograms, the H^+ is roughly concealed under the plot of the $t\bar{t}$. However, at high enough value for the H^+ truth mass (1000 GeV) we see a clear separation between the signal and the background with the caveat of having the signal distribution flatter to be recognized efficiently. This can be improved more by having a better background distribution since the histogram here has a large number of fluctuations which can be solved by running through more events. Lastly we can deduce here that having a higher truth mass, results in a clearer separation between the signal and the background process at the cost of the shape of the signal varying along the increase.

8 Conclusions

The project fulfilled its objective which is to show a mass reconstruction plot of the H^+ using a rigorous statistical weighting average technique from a numerous possible parton-jet assignment combinations per event. Although the project has done so much, more work could still be done on the topic to improve the data and its analysis. More events can be used for a better, smooth distribution while improving the binning of the histograms.

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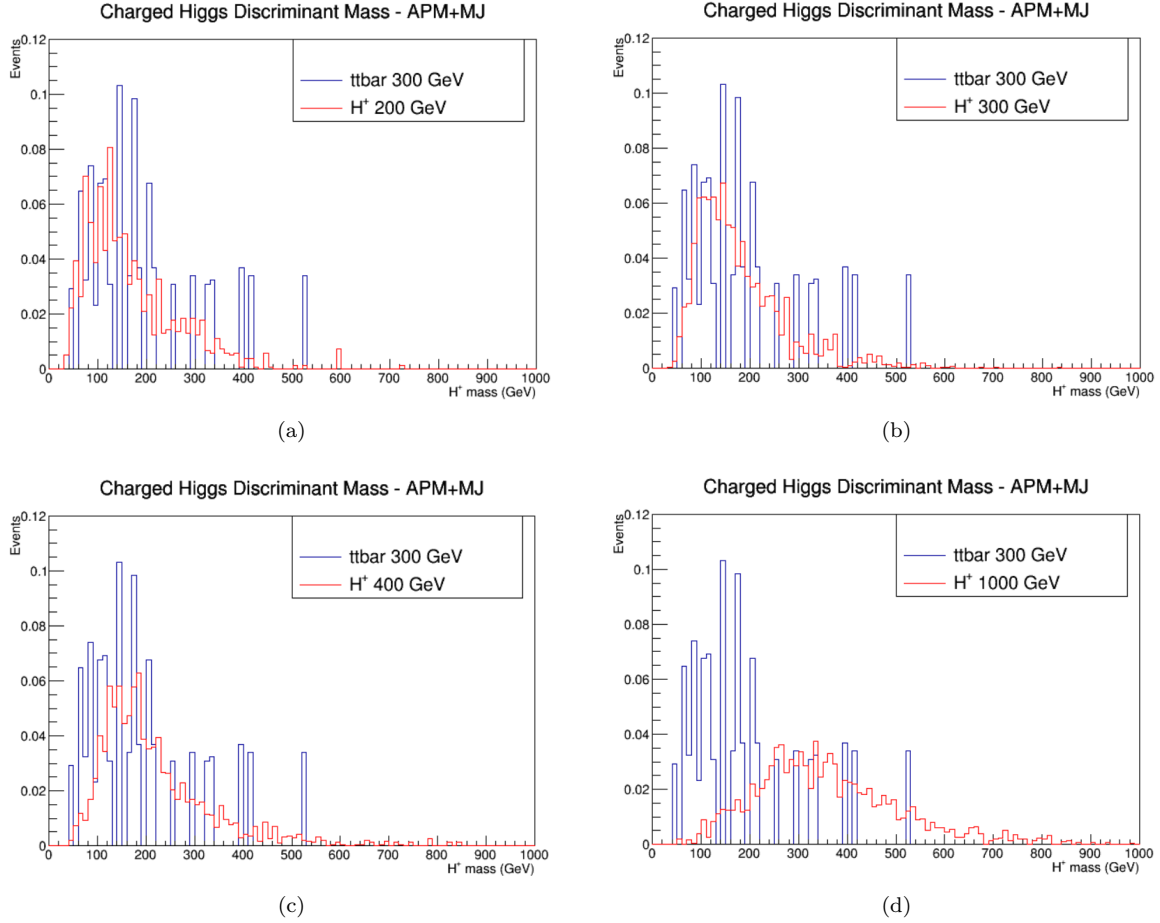


Figure 8: Weighted average H^+ mass per single event with the signal and background ($t\bar{t}$ Mean: 186.271) process plots in the (a) 200 GeV truth mass case, (b) 300 GeV truth mass case, (c) 400 GeV truth mass case and (d) 1000 GeV truth mass case

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