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Διατμηματικό Πρόγραμμα Μεταπτυχιακών Σπουδών

«Φυσική και Τεχνολογικές Εφαρμογές»

2-Dimensional Mass Reconstruction in Asymmetric Topologies with Two Invisible Particles

ΜΕΤΑΠΤΥΧΙΑΚΗ ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

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Αθήνα, Οκτώβριος, 2024

ΠΕΡΙΛΗΨΗ

Η παρούσα διπλωματική εργασία επικεντρώνεται στην ανακατασκευή μάζας σε ασύμμετρες τοπολογίες με δύο αόρατα σωματίδια, όπως τα νετρίνα ή άλλα υποψήφια σωματίδια σκοτεινής ύλης. Η μέθοδος έχει χρησιμοποιηθεί μέχρι στιγμής με επιτυχία σε συμμετρικές τοπολογίες και επιτρέπει τη δισδιάστατη ανακατασκευή μάζας του συστήματος.

Οι τελικές καταστάσεις με ελλείπουσα ενέργεια είναι σημαντικές, επειδή προβλέπονται από θεωρίες πέρα από το Καθιερωμένο Πρότυπο (BSM). Ωστόσο, η μελέτη τους αποτελεί πρόκληση, καθώς η αναζήτηση νέων σωματιδίων είναι αρκετά πιο περίπλοκη σε σχέση με αυτή των γνωστών σωματιδίων. Παρά το γεγονός ότι συνηθίζεται σε τέτοιες καταστάσεις, η αναζήτηση να γίνεται συχνά στην ουρά της κατανομής της ελλείπουσας ενέργεια, το σχήμα της κατανομής του υποβάθρου είναι παρόμοιο με το σχήμα κατανομής του σήματος, καθιστώντας δύσκολη τη διάκριση μεταξύ τους. Επιπλέον, τα αποτελέσματα βασίζονται συχνά σε θεωρητικές παραδοχές, οι οποίες μπορεί να οδηγήσουν σε λανθασμένα συμπεράσματα.

Από την άλλη, η μάζα αποτελεί μία από τις πιο σημαντικές παραμέτρους στη φυσική των στοιχειωδών σωματιδίων, καθώς είναι ένα φυσικό χαρακτηριστικό που μπορεί να χρησιμοποιηθεί για την περιγραφή των ιδιοτήτων τους. Η επιλογή του επιπέδου μάζας για αναζητήσεις κορυφών είναι λογική, καθώς σήματα που μπορεί να κρύβουν νέα φυσική τείνουν να εμφανίζονται σε συγκεκριμένες τιμές μάζας, προσφέροντας αυξημένη ευαισθησία σε σχέση με άλλες κινηματικές παραμέτρους. Ακόμα, το υπόβαθρο στις κατανομές μάζας είναι συχνά ομαλό, επιτρέποντας στο σήμα να ξεχωρίζει.

Η μέθοδος που προτείνει η [2] βασίζεται στη δισδιάστατη ανακατασκευή μάζας για τελικές καταστάσεις με δύο αόρατα σωματίδια, που επιτρέπει την αναζήτηση κορυφών στο δισδιάστατο επίπεδο. Η επιλογή αναζήτησης κορυφών σε δύο διαστάσεις οφείλεται στο γεγονός ότι μελετώνται τοπολογίες με δύο άγνωστα σωματίδια.

Αρχικά, υπάρχει αναλυτική λύση για την διάσπαση ενός ζεύγους τοπ κουαρκ σε δύο λεπτόνια και δύο αόρατα σωματίδια, τα νετρίνα. Αυτή η αναλυτική λύση υπολογίζει τις ορμές των αόρατων σωματιδίων με μεγάλη ακρίβεια και επιτρέπει την πλήρη ανακατασκευή του συστήματος. Η αναλυτική λύση καταλήγει σε ένα πολυώνυμο τετάρτου βαθμού και μπορεί να δώσει έως τέσσερις λύσεις για ένα ζεύγος μαζών. Η αναλυτική λύση χρησιμοποιείται ως εργαλείο για την ανακατασκευή μάζας.

Στη συνέχεια, δοκιμάζεται η ανακατασκευή μάζας σε μία γνωστή συμμετρική τοπολογία του Καθιερωμένου Προτύπου, αυτή της δι-λεπτονικής διάσπασης ενός ζεύγους τοπ κουάρκ ως απόδειξη. Από τη στιγμή, που η αναλυτική λύση επιτρέπει την πλήρη ανακατασκευή του συστήματος και παρέχει πληροφορίες για την ενέργεια και την τρίτη συνιστώσα της ορμής των νετρίνων, είναι μια καλή ιδέα να ελεγχθεί όλο το επίπεδο μαζών για πιθανές λύσεις. Από αυτό τον έλεγχο προκύπτει μία περιοχή στο δισδιάστατο επίπεδο μαζών στην οποία μπορεί να λυθεί ένα ζεύγος μαζών (επιλυσιμότητα). Στη συνέχεια, με τη βοήθεια των PDFs κάθε σημείο μαζών αποκτά ένα βάρος το οποίο μπορεί να προστεθεί στην κατανομή επιλυσιμότητας. Για ένα γεγονός και για μία λύση, δημιουργείται μία τέτοια κατανομή. Από όλες τις κατανομές επιλυσιμότητας που προκύπτουν για ένα γεγονός επιλέγεται ένα σημείο μαζών, αυτό με το μεγαλύτερο βάρος. Επομένως, για ένα γεγονός προκύπτει ένα μοναδικό ζεύγος μαζών. Αν επαναληφθεί η διαδικασία αυτή για πολλά γεγονότα είναι δυνατή η δισδιάστατη ανακατασκευή μάζας, η οποία για τη συμμετρική τοπολογία ήταν επιτυχημένη.

Στη συνέχεια, η εργασία επεκτείνεται στη διερεύνηση τοπολογιών που έχουν ως τελική κατάσταση την ίδια με την συμμετρική αλλά οι μάζες των συμμετεχόντων σωματιδίων διαφέρουν. Οι τοπολογίες που δοκιμάστηκαν ήταν δύο και βασίζονται στο Rho Model [4][5][6], ένα μοντέλο που προβλέπει ένα νέο υποθετικό βαρύ τοπ κουάρκ. Η μία τοπολογία προέβλεπε ένα άγνωστο σωματίδιο ενώ η δεύτερη δύο. Κάνοντας τις αναγκαίες αλλαγές στον αλγόριθμο, η ανακατασκευή μάζας είναι εφικτή. Και στις δύο περιπτώσεις, τα αποτελέσματα έδειξαν ότι η μέθοδος μπορεί να υπολογίσει επιτυχώς τις μάζες των άγνωστων σωματιδίων.

Συμπερασματικά, η αναλυτική λύση μπορεί να εφαρμοστεί και να χρησιμοποιηθεί για την ανακατασκευή μαζών σε ασύμμετρες τοπολογίες, όπως και σε συμμετρικές. Αυτή η μέθοδος είναι κατάλληλη για την αναζήτηση νέων σωματιδίων, καθώς δεν απαιτεί καμία εκ των προτέρων γνώση των μαζών τους και είναι ανεξάρτητη από θεωρητικές υποθέσεις, εκτός από την τοπολογία του συστήματος.

2-Dimensional Mass Reconstruction in Asymmetric Topologies with Two Invisible Particles

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***Abstract*— The two-dimensional mass reconstruction of an asymmetric topology with two invisible particles from Beyond the Standard Model (BSM) scenarios is presented. The method has been used so far successfully in symmetric topologies and allows in this case two-dimensional mass reconstruction of the system.**

I. INTRODUCTION

Missing energy final states are an interesting case as they are predicted by well-motivated BSM theories. Exploring final states with missing energy in pursuit of new physics presents a formidable challenge, significantly more intricate than the search for particles with established properties. This missing energy arises from undetectable particles such as SM neutrinos (e.g heavy top partners) or other hypothetical particles such as WIMPs and other dark matter candidates.

Even though, in final states with invisible particles the search is usually performed using the tail of a missing energy related distribution, the background processes have a similar shape, making it challenging to distinguish them from signal. Also, the interpretation of results in the tail region is usually based on the assumptions and limitations of theoretical models leading to false conclusions. Even if a discovery is confirmed, only a constrained amount of supplementary information regarding the new physics would be forthcoming. Ideally, the search performance remains unaffected by the model or, realistically, exhibits as much model independence as possible.

On the other hand, mass is one of the most significant quantities in elementary particles since it is a natural parameter for characterizing particle properties. Selecting mass space for resonance searches might be a reasonable path [2]. Peaks or excesses in the mass spectrum are localized. Resonance signals, also, tend to be concentrated at specific mass values, leading to enhanced sensitivity in the mass space compared to other kinematic variables. Moreover, in many cases, background processes exhibit relatively smooth distributions in the mass space, allowing resonant signals to stand out more prominently making their extraction easier. Historically, also, many groundbreaking discoveries in particle physics, such as the discovery of the Higgs boson, have been made through bump hunting search. The method proposed in [2] suggests employing a two-dimensional mass reconstruction of the final states involving two invisible particles, which allow bump-hunting search in two dimensions.

The subsequent sections outline the procedure for conducting a 2-Dimensional mass reconstruction in final states characterized by two invisible particles. Section II presents the symmetric topology case using a dilepton top pair system as a proof of principle and explains all the steps necessary. Then in Section III, an asymmetric topology is presented. The employment of two-dimensional mass reconstruction facilitates these searches via bump hunting giving a single entry per event, harnessing all the advantages offered in terms of discovery. Finally, Section IV is dedicated to conclusions.

II. The Method for Symmetric Topologies

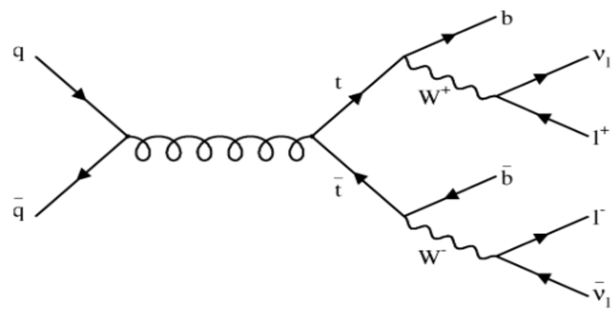

Figure 1. Feynman diagram of the top pair dilepton decay.

In the benchmark top pair topology (Figure 1) for final states with two invisible particles, an analytical solution of the system of equations describing the top pair dilepton kinematics exists [2]. Analytical Solution is an algorithm that takes input the masses of top quarks, W bosons, b quarks, the detector's measured momenta of visible particles as well as missing energy ($E_{miss,x}$, $E_{miss,y}$). The output produced is the momenta of the two neutrinos. Each solution allows complete reconstruction of the event kinematics, meaning that the energy of the system E and the p_z component of momentum can be computed. Thus, the fractions of beam energy of the two partons participating in the scattering are calculable for every solvable event:

$$X_{1,2} = (E \pm P_z)/\sqrt{s}.$$

These fractions are incorporated into Parton Distribution Functions (PDFs), assigning a weight to each mass pair of W boson and top quark. The mass point and solution with the highest weight is selected. Thus, for a single event one mass point of top quark and W boson is estimated.

As mentioned, there is an analytical solution of the system of equations describing the top pair dilepton kinematics. The topology of such a system is presented in Figure 1. The system of equations describing the kinematics of top-pair dilepton events can be expressed by two linear and six nonlinear equations (Appendix). From the system of these equations arises a quartic polynomial representing the z component of neutrino's momentum [1]. In order for this polynomial to be solved the masses of top quarks, W bosons, b quarks must be given as an input. Analytical solutions, also, requires the momenta of visible particles and the missing energy components. The algorithm has as an output the neutrino's momentum. The number of real solutions can be either 0, 2, or 4. However, a combinatorial problem occurs since it is unknown which lepton corresponds to each bottom quark for the event. So, two combinations of final states need to be considered, leading to two sets of solutions, each providing a maximum of four solutions. Each event can have up to 8 solutions for neutrino's momentum. Each solution allows the full reconstruction of the top pair system kinematics.

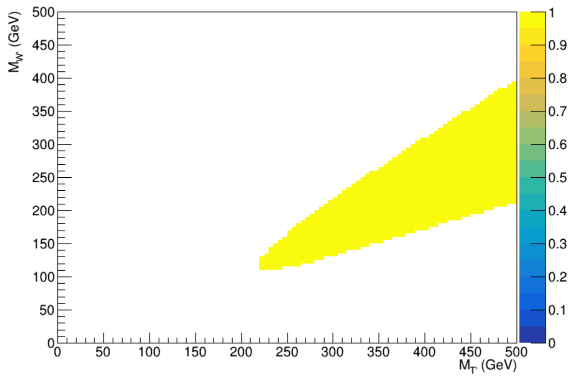

Figure 2. Solvability distribution in the $M_{T'}$ and $M_{W'}$ plane for one of the possible solutions for a single dilepton top pair event.

Searching configurations involving two invisible particles doesn't necessitate in symmetric topologies prior knowledge of their masses, such information emerges as an outcome. Since the algorithm of analytical solution allows to enter any pair of masses for top quark and W boson, each combination of them can be examined for potential solutions. So, the mass plane of top quark and W boson was scanned in steps of 5 GeV, for every single solution, to locate the area where the event can be solved. An example of solvability (solution area) for a single event for one solution is presented in Figure 2. The area provides a boundary in the lower mass region for the possible masses of top quark and W boson, as below these masses the event is not solvable [2].

Each solution provided by the algorithm allows complete reconstruction of the kinematics of the event, meaning that the energy E and the p_z component top pair system are computable. These quantities carry high importance since they can be used for the estimation of fractions of beam energy of the two partons participating in the hard scattering X_i, i =1,2. This further allows a weight per mass point and solution to be estimated. By utilizing fractions X_1, X_2, a PDF associated with each parton can be calculated [7]. Then the two probability densities are multiplied to give an event weight per mass point per solution for a single event. The PDFs impose an energy restriction, setting an upper limit on the masses produced due to the finite collision energy, as the center of mass energy of the partons involved in the hard scattering must be lower than the LHC collision energy [2]. For the estimation of the PDF values the LHAPDF-6.1.2 interface was used and the PDF set CT10 [2],[3],[7]. For each solution, a weighted two-dimensional mass distribution is obtained for a single event. An example of such distribution is presented in Figure 3. Thus, for a single event 8 weighted two-dimensional distributions are created, one for each solution. The mass point with the highest weight from all 8 distributions is selected. The algorithm gives a single pair of masses of top quark and W boson for a single event.

The top pair dilepton decay (Figure 1) can be used as a proof of principle for the proposed method since it is a well-established process.

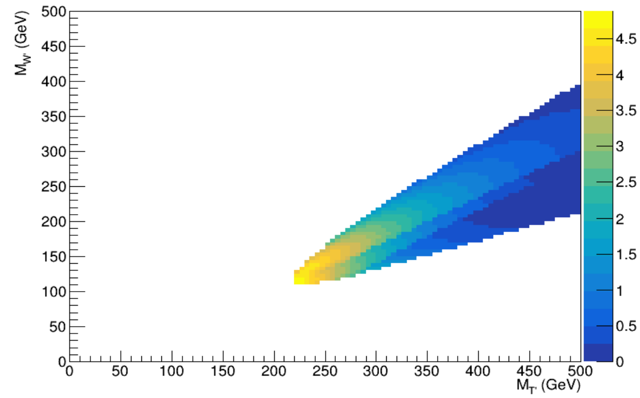

Figure 3. PDF weighted solvability distribution in the $M_{T'}$ and $M_{W'}$ plane for one of the possible solutions for a single dilepton top pair event.

Initially, events were generated using Madgraph5 at a collision energy of 13 TeV, followed by hadronization implemented via Pythia8 [8]. These events were further processed through Delphes [9] software for a CMS like detector simulation and reconstruction. Finally, an event selection was applied, requiring 2 leptons, 2 jets and large missing transverse energy. The dilepton top pair events applied for this topology were fully simulated.

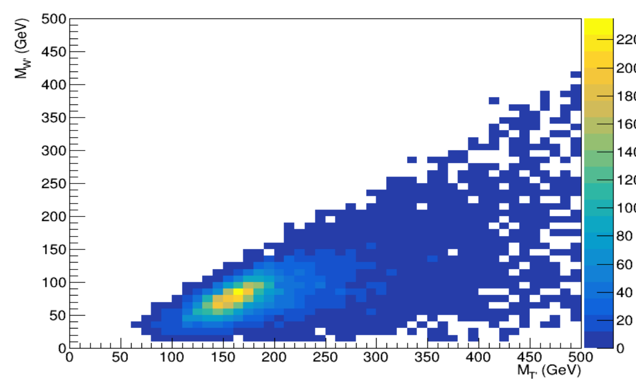

Figure 4. Two-dimensional reconstructed mass distribution for the symmetric topology of simulated top pair events.

Applying the above method in a dilepton top pair sample the two-dimensional reconstructed mass distribution formed is presented in Figure 4. The masses of W boson and top quark lie close to their generated values.

The main conclusion is that the method is effective for a known process of the Standard Model and most important does not require prior knowledge of the particles' masses.

III. Asymmetric Topologies

The algorithm of analytical solution itself does not assume that the masses of the particles of the two branches are necessarily symmetric. Therefore, it seems reasonable to test the possible application of the method to asymmetric topologies predicted by BSM theories.

Initially, the analytical solution for asymmetric topologies was tested with a toy monte carlo. The toy monte carlo events were solved successfully at per mill level for the symmetric topology. The toy monte carlo works by creating a top quark with specific energy with random angles thita, phi in a back-to-back configuration with the antitop quark in the lab frame. Then, the top quark decays in its rest frame isotropically to W boson and b quark and boosted in the lab frame. The identical procedure was followed for the decay of W bosons to leptons and neutrinos. Tests of the algorithm for asymmetric topologies using this toy monte carlo were successful at per mill precision similar to symmetric topology. These results indicate that the analytical solution works for both symmetric and asymmetric topologies.

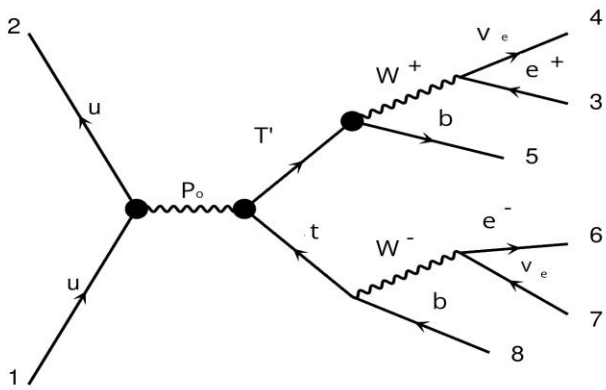

Figure 5. Feynman diagram of an asymmetric topology with one unknown particle.

Since the method is effective to any topology like the dilepton top decay, for the asymmetric case the following process was examined:

$$pp \to Z/Po \to tT' \to WbW\bar{b} \to l\nu l\bar{\nu} \quad (1)$$

where T' is a new hypothetical heavy top partner. The process (Figure 5) is predicted by the Rho model [5][6]. This model provides a description for spin-1 resonances (P_o particle). The P_o particle is represented by a fourplet and transforms as vector triplets [(3,1) and (1,3)] under the SO(4) ~ $SU(2)_L \times SU(2)_R$ symmetry, or as a singlet (1,1) under the abelian group $U(1)_x$. The Rho model, also, predicts the (T, B) doublet with the same quantum numbers as top and bottom quarks and the $X_{5/3}$, $X_{2/3}$ doublet with an exotic particle of charge 5/3 and a second top-like resonance, $X_{2/3}$[5][6].

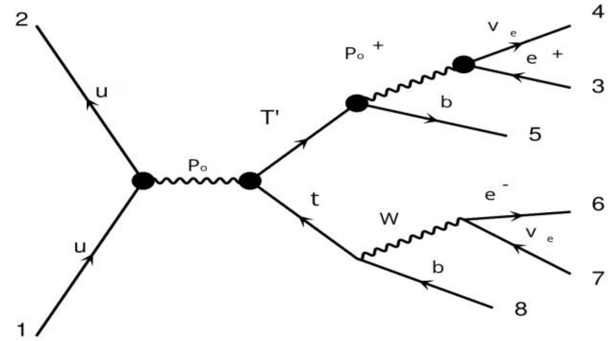

Figure 6. Feynman diagram of an asymmetric mass dilepton decay with two unknown paricles.

A sample of events was generated with Madgraph5 at a collision energy of 13 TeV importing of Rho Model [4],[5],[6]. Events were generated with T' mass set at 700 GeV and W mass set at 80 GeV. Initially, only particles of the hard process were examined.

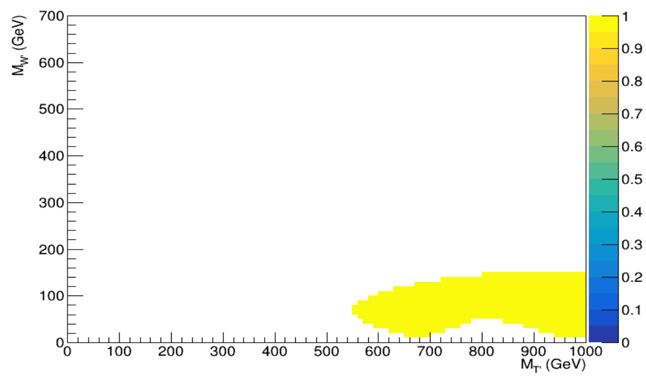

Figure 7. Solvability distribution in the $M_{T'}$ and $M_{W'}$ plane for one of the possible solutions of a single event for the asymmetric topology.

These events were used to evaluate where the analytical solution algorithm successfully solves top quarks and the hypothetical new T' quark with varying masses. The fraction of events where no solution was found, or no solution coincides with the generated neutrino-antineutrino momenta to real precision is at per mill level as in the symmetric case [1].

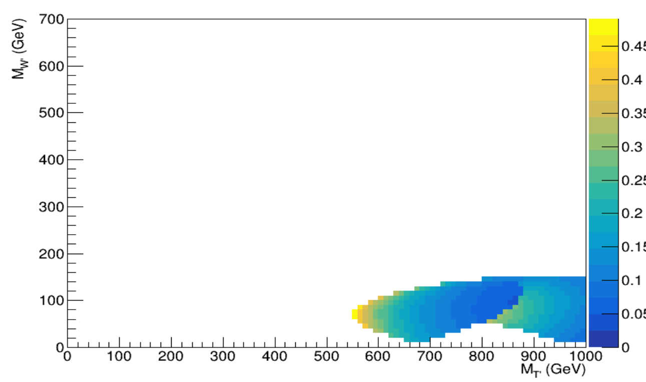

Figure 8. PDF weighted solvability distribution in the $M_{T'}$ and $M_{W'}$ plane for one of the possible solutions of a single event for the asymmetric topology.

First results refer to the solvability of a single event. It's worth mentioning that due to the combinatorics of asymmetric case four sets of solutions had to be computed instead of two. In this case, the maximum number of solutions was 16 since each set can give up to 4 solutions. For every event, 16 different two-dimensional solvability distributions were produced. Similar to the symmetric case, for each solution a weighted two-dimensional mass distribution is obtained for a single event. So, solvability per solution and solvability per solution weighted with PDF are demonstrated in Figures 6 and 7, respectively. For a single event from all the 16 distributions, one mass point was selected, the one with the highest PDF weight. Since for each event a single mass point is produced the final two-dimensional reconstructed mass distribution is presented in Figure 8. The mass plane aligns with the expectations, meaning that T' and W masses lie close to their generated values.

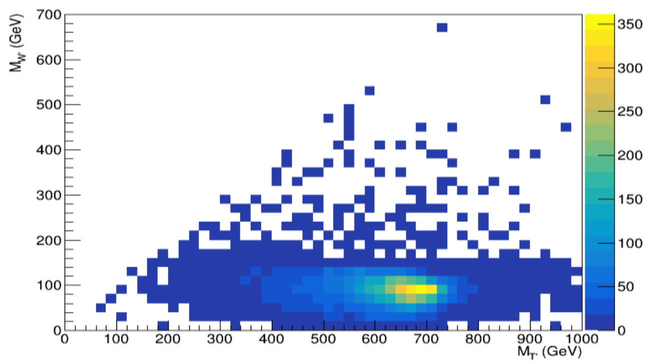

Figure 9. Two-dimensional reconstructed mass distribution for the asymmetric (1) topology for generated events (hard process particles).

Another process based on the same model was also studied:

$$pp \rightarrow P_o \rightarrow T'\bar{t} \rightarrow P_o^+ bW^-\bar{t} \qquad (2)$$

again, the events were generated using Madgraph5 at a collision energy of 13 TeV. Masses of T' and P^+ were generated to 700 GeV and 300 GeV, respectively (Figure 6). The two-dimensional mass reconstruction distribution for this process can be seen in Figure 9. The mass ranges for the particles of interest are compatible with their generated values.

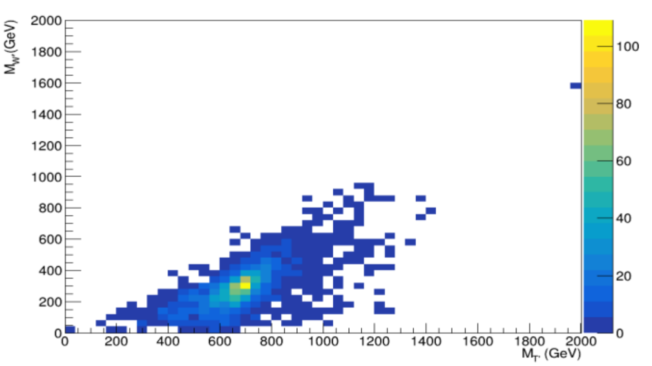

Figure 10. Two-dimensional reconstructed mass distribution for the asymmetric (2) mass topology for generated events (hard process particles).

Another study for both asymmetric topologies was performed using fully simulated events. The generated events were hadronized via Pythia8, simulation and reconstruction through Delphes. The simulated events were selected based on the properties of the topologies. The number of leptons (muons or electrons) in the final state must be two and their transverse momentum has to be greater than 30 GeV. Also, two jets are required, and their transverse momentum must be greater than 30 GeV. Moreover, Figures 10 and 11 for the asymmetric topologies (1) and (2) respectively represent the mass distribution of fully simulated events. In both cases, the masses of unknown particles lie close to their generated values.

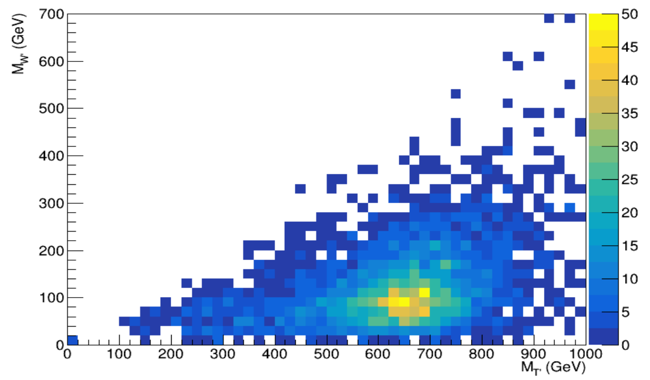

Figure 11. Two-dimensional reconstructed mass distribution for the asymmetric (1) topology for fully simulated events.

In conclusion, the method is effective for topologies with asymmetric branches, yielding the expected mass values for the particles involved in the process.

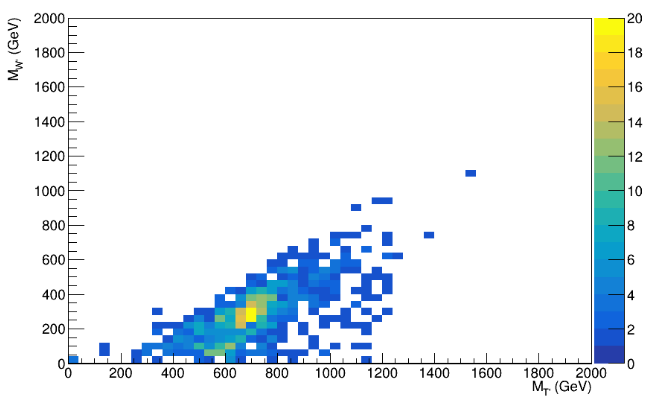

Figure 12. Two-dimensional reconstructed mass distribution for the asymmetric (2) topology for fully simulated events.

IV. Conclusion

Analytical solutions for the dilepton top pair dilepton decay are also applicable to asymmetric mass topologies. These solutions can then be employed for reconstructing the masses of asymmetric topologies similarly to symmetric topologies.

It is worth mentioning that the method is suitable for searching for new particles, since it does not necessitate any a-prior knowledge of their masses. Mass plane, also, allows bump hunting and provides much more information about the new particles. Finally, the method is as model independent as possible.

V. APPENDIX

Kinematics of the top pair dilepton decay:

$$E_{miss,x} = p_{v_x} + p_{\bar{v}_x}$$
$$E_{miss,y} = p_{v_y} + p_{\bar{v}_y}$$
$$E_v^2 = p_{v_x}^2 + p_{v_y}^2 + p_{v_z}^2$$
$$E_{\bar{v}}^2 = p_{\bar{v}_x}^2 + p_{\bar{v}_y}^2 + p_{\bar{v}_z}^2$$
$$m_{W^-}^2 = (E_{l^-} + E_{\bar{v}})^2 - \sum_{i=1}^{3} \left(p_{l_i^-} + p_{\bar{v}_i}\right)^2$$
$$m_{W^+}^2 = (E_{l^+} + E_v)^2 - \sum_{i=1}^{3} \left(p_{l_i^+} + p_{v_i}\right)^2$$
$$m_{\bar{t}}^2 = \left(E_{\bar{b}} + E_{l^-} + E_{\bar{v}}\right)^2 - \sum_{i=1}^{3} \left(p_{\bar{b}_i} + p_{l_i^-} + p_{\bar{v}_i}\right)^2$$
$$m_t^2 = (E_b + E_{l^+} + E_v)^2 - \sum_{i=1}^{3} \left(p_{b_i} + p_{l_i^+} + p_{v_i}\right)^2$$

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