Distinguishing Dark Matter Stabilization Symmetries at Hadron Colliders with Mass Variables

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Abstract

1 Background

Cosmological and astrophysical observations, yet all gravitational, suggest that there exists stable matter, so-called dark matter (DM), in our universe, which is exerting gravity but hardly detectable in relevant experiments. The stability of DM indicates that DM needs to be either massless or protected by a new symmetry (henceforth called DM stabilizing symmetry) preventing its decay. It turns out that cosmological consideration suggests that massless particles be unlikely to constitute a dominant portion of the DM, motivating DM candidates with a sizable mass. While a massive particle, in general, may decay into lighter particles, the charge conservation associated with the symmetry ensures the stability of DM.

There is a tremendous amount of effort in the search for DM candidates and it also comprises collider experiments. DM is, by definition, hard to be detected at colliders such as the LHC. So, its existence may be inferred from (visible) Standard Model (SM) particles emitted from a decay chain of a heavier state (henceforth denoted as a DM partner) into DM. One compelling situation to be considered is a pair creation of DM partner particles followed by decay of each of those into DM particles. Different symmetries protecting the DM stability may allow different event topologies for the decaying process of the pair-produced partners. Although many well-motivated new physics models accompany a Z_2/parity-type symmetry as the DM stabilization symmetry, Z_2 is not the only option. My CERN summer student programme was devoted to constructing a systematic method for determining whether or not a given decay process is induced from a Z_2 symmetry, with limited information encoded in relevant visible states.

2 Contribution

2.1 Decay event data reproducition

As a preparatory work, I reproduced M_{T2}, M_2, and transvere momentum variable distributions of different subsystems in a well-known $t\bar{t}$ decay process. Denoting (anti) bottom quark as b and (anti) electron as l, the distributions in Figure 1 and Figure 2 were yielded, and they matched previously known distribution patterns.

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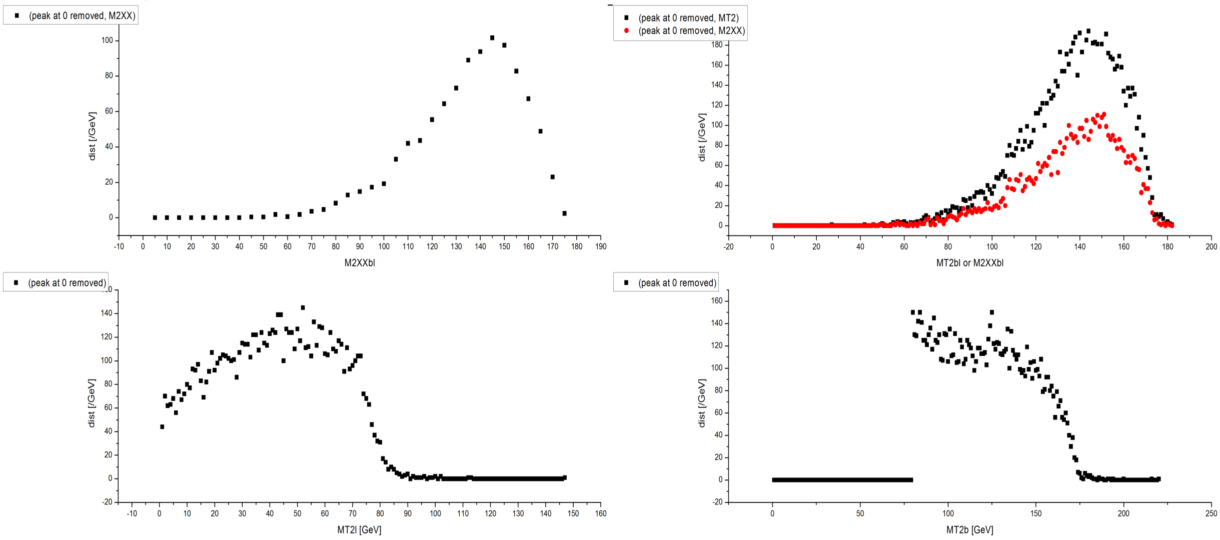


Figure 1: Distributions of transverse mass variables $M_{2XX}^{(bl)}$ (with $m = 0$), $M_{2XX}^{(bl)}$ together with $M_{T2}^{(bl)}$ (with $m = 0$), $M_{T2}^{(b)}$ (with $m = 80$), and $M_{T2}^{(l)}$ (with $m = 0$) in clockwise direction from the top left one, where m denotes the test mass (in GeV) used for each variables

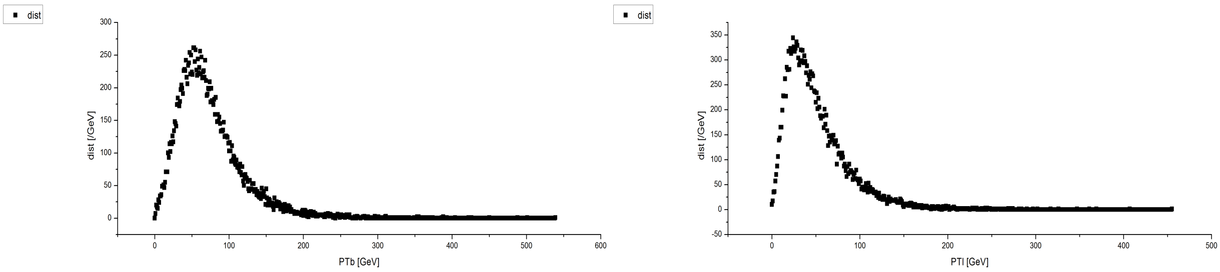


Figure 2: Distributions of transverse momentum variables $p_T^{(b)}$, and $p_T^{(l)}$ from left to right

Note that the distributions are not unit normalized. One can observe that $M_{T2}^{(bl)}$ and $M_{2XX}^{(bl)}$ variables have the same endpoints, confirming the fact that these two variables coincide event-wise. The $M_{T2}^{(bl)}$, $M_{T2}^{(b)}$, and $M_{T2}^{(l)}$ variables have their maximum endpoints near $170GeV$, $170GeV$, and $80GeV$, respectively. Since the top quark and the W boson have masses $172.44GeV$ and $80.385GeV$, the endpoint results coincide with each of the mother particle mass of each subsystem as it is theoretically expected.

2.2 T_2 signature - Endpoints of ranked $M_{T2}^{(a)}$ variable

For a two-chain decaying process under consideration here, there is a general observation that M_{2CC} distributions exhibit an overflow beyond the maximum endpoint in the M_{T2} distribution for the same system, if the underlying physics differs from the event topology that the M_{2CC} variable hypothesizes: 1) symmetric and 2) existence of on-shell intermediary states.

This general observation can be used to make a distinction of Z_2 DM stabilizing symmetry from the other larger symmetries. Under Z_2 DM stabilizing symmetry, when a DM candidate partner decays into two SM particles (visible particles) and one DM candidate particle, there are two distinct event topology for a decay process of pair-created DM candidate partners: T_1 and T_2 as in Figure 3.

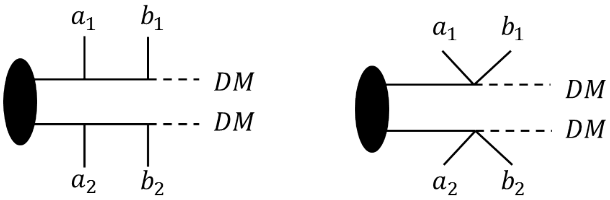


Figure 3: T_1 and T_2 event topologies, respectively, from left to right. *DM* denotes a DM candidate, and $a_{1,2}$ and $b_{1,2}$ denote the first and second visible particles produced from chain $1,2$, respectively.

Notice that T_1 and T_2 are symmetric under chain swapping. On the other hand, under larger DM stabilizing symmetries, there are some event topologies exhibiting asymmetry under the chain swapping, and so the $M_{2CC}^{(ab)}$ distribution would show an overflow beyond the maximum endpoint in the $M_{T2}^{(ab)}$ distribution. One example of such asymmetric event topology arising from Z_3 DM stabilizing symmetry is T_3 in Figure 4.

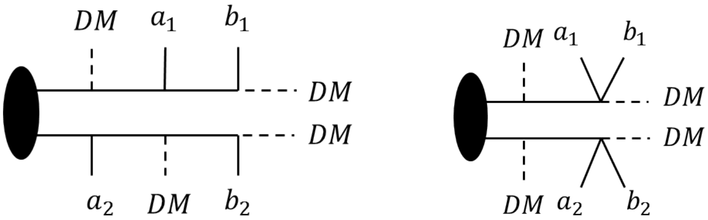


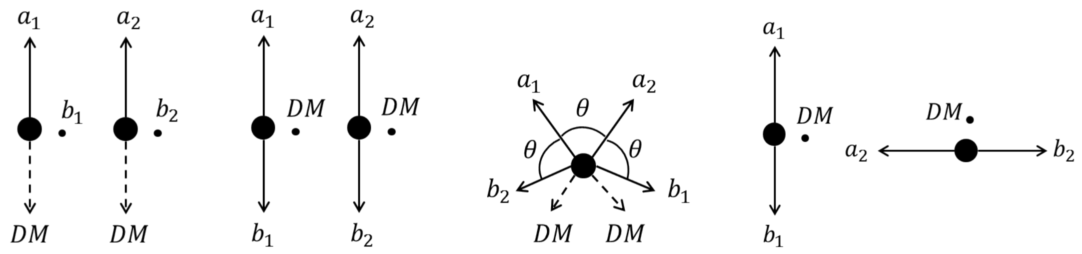
Figure 4: Left: T_3 event topology. *DM* denotes a DM candidate, and $a_{1,2}$ and $b_{1,2}$ denote the first and second visible particles produced from chain $1,2$, respectively. Right: An event topology arising from Z_3 DM stabilizing symmetry having a subsystem equivalent to T_2.

However, this $M_{2CC}^{(ab)}$ endpoint test alone cannot distinguish Z_2 symmetry from the others. That is because $M_{2CC}^{(ab)}$ distribution exhibits the overflow in T_2 topology as well, as there is no on-shell intermediary state in the *ab*-subsystem, and this argument based on the general observation was confirmed by an event sample I generated. Thus it was crucial to find a method from observation of visible particles which distinguishes T_2 from other event topologies.

This may be rather easier when the visible particles a and b are distinguishable from the observation. In such cases, no matter one set the a-subsystem as $\{a_1, a_2\}$ (ie. a correct combination) or as $\{b_1, b_2\}$ (ie. a wrong combination), $M_{T2}^{(a)}$ distribution for T_2 event would come out to be the same due to the fact that T_2 is topologically identical under the operation of $a_{1,2} \leftrightarrow b_{1,2}$. Because this phenomenon is heavily relying on the topological property mentioned above, this can be understood as a sign of T_2 or at least of an existence of a subsystem equivalent to T_2 (see Figure 4). But this observation is unavailable for the cases in which the visible particles are indistinguishable even when the partition of the visible particles $(\{a_1, b_1\}, \{a_2, b_2\})$ into the chain $1,2$ is known.

To cover the cases, I introduced a new T_2 signature dealing with every possible combination for a-subsystem where the visible particles are indistinguishable and the partition is known. There are four possible combinations for the a-subsystem: $\{a_1, a_2\}$, $\{a_1, b_2\}$, $\{b_1, a_2\}$ and $\{b_1, b_2\}$. Thus when one ranks the $M_{T2}^{(a)}$ variable by its magnitude for each of these combinations, one yields four ranked $M_{T2}^{(a)}$'s for each event: $M_{T2}^{(a),4} \leq M_{T2}^{(a),3} \leq M_{T2}^{(a),2} \leq M_{T2}^{(a),1}$. Then one gets a distribution for each $M_{T2}^{(a),j}$ ($j = 1,2,3,4$), and can get its maximum endpoint $M_{T2}^{(a),j,\max}$. The new T_2 signature is the exact relationships between the maximum endpoints $M_{T2}^{(a),j,\max}$ $(j = 1,2,3,4)$.

Each maximum endpoint $M_{T2}^{(a),j,\max}$ was obtained by coming up with a specific event configuration which maximizes $M_{T2}^{(a),j}$. For each j, the specific event configuration which may maximize $M_{T2}^{(a),j}$ was searched primarily among the configurations with DM candidate partners pair-created at rest yielding $M_{T2}^{(a),1} = \cdots = M_{T2}^{(a),j}$. Then the exactness of the maximizing configuration was checked by scanning the values of $M_{T2}^{(a),j}$ for T_2 events generated by *phase space generator* built in *Root*. The maximizing configuration for each j are illustrated in Figure 5.



(a) $j = 1$ (b) $j = 2$ (c) $j = 3$ (d) $j = 4$

Figure 5: $M_{T2}^{(a),j}$ maximizing event configurations (Note that the θ is not arbitrary.)

For every $j = 1,2,3,4$, the maximum endpoint $M_{T2}^{(a),j,\max}$ obtained from each maximizing configuration takes the form of (1):

$$M_{T2}^{(a),j,\max} = \sqrt{\frac{A_j}{2}} + \sqrt{\frac{A_j}{2} + m^2} \tag{1}$$

where m is the test mass for computing M_{T2}^{a} variable and A_j's are given by

$$\begin{aligned}
A_1 &= \frac{(m_A - m_{DM})^2}{2}\left(1 + \frac{m_{DM}}{m_A}\right)^2 \\
A_2 &= \frac{(m_A - m_{DM})^2}{2} \\
A_3 &= \max_{y \in \left[0, \sqrt{1 - \frac{m_{DM}^2}{m_A^2}}\right]} \frac{\left(m_A - \sqrt{m_A^2 y^2 + m_{DM}^2}\right)^2}{4(1-y)(1-y^2)} \\
A_4 &= \frac{(m_A - m_{DM})^2}{4}
\end{aligned}$$

with m_A being the mass of the DM candidate partner.

These relationships work as a T_2 signature because A_2 and A_4 are connected by a factor of 2, and A_1 and A_2 independent. These enable one to measure each A_j by measuring $M_{T2}^{(a),j,\max}$, solve A_1 and A_2 for m_A and m_{DM}, and check whether the measured A_2 and A_4 satisfy $A_2 = 2A_4$ and whether the A_3 calaulated from the above formula matches its measured value. Since the maximizing configurations found for $M_{T2}^{(a),1}, \ldots, M_{T2}^{(a),4}$ are relying on the fact that a_i particle and b_i (i=1,2) particle are comming from the same off-shell scattering point, this test enables us to isolate T_2 event topology from any other event topologies.

In order for this new T_2 signature to be applicable to general case where the DM candidate partners are not pair-created at rest, the relationships among $A_1, \ldots, A_4$ need to be invariant under a back-to-back boost of the two pair-created partner particles on a plane (called *transeverse plane*) followed by a Lorentz boost along a direction perpendicular to the plane. In fact, it could be easily check that not only their inter-relationships but also the $A_1, \ldots, A_4$ themselves are invariant under such combinations of Lorentz boosts.

2.3 Simulation and Analysis

I developed a program which enables a user to compute M_{T2} and M_2 variables for every possible decay topology (carrying two visible particles per decay chain, and at most three-body decay permitted) of pair-created DM candidate partners either under Z_2 or Z_3 DM stabilizing symmetry based on *OptiMass* and *Root*. Here I attach a graph (see Figure 6) exhibiting the overflow of $M_{2CC}^{(ab)}$ distribution beyond the maximum endpoint in $M_{T2}^{(ab)}$ distribution for T_3 event topology generated by the program as an example.

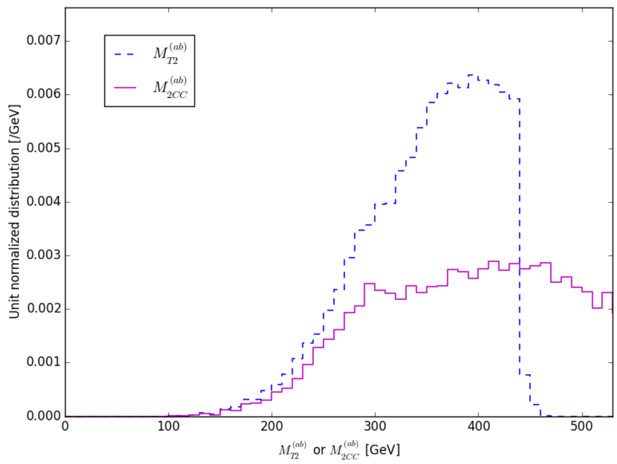


Figure 6: Overflow of $M_{2CC}^{(ab)}$ distribution beyond the endpoint in $M_{T2}^{(ab)}$ distribution appearing in T_3 event topology

3 Future prospect

While developing a systematic method of distinguishing a Z_2 stabilizing symmetry from larger symmetries (in particular, Z_3) by exploring event topologies absent in Z_2 models and observing endpoint behaviors of M_{T2} and M_2 variables, we have found challenging problems regarding the analytic forms of $M_{2CC}^{(ab)}$ endpoint and of ranked M_{T2} variables' endpoint. I expect that understanding these problems will expand existing insights on underlying meaning of M_{2CC} and M_{T2} variables. Finally, we are planning to publish any further acheivement on these problems together with what has been done during this Summer Student programme in the form of a paper.