Using M_{T2} to Distinguish DM Stabilization Symmetries

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K. Agashe, DK, D. G. Walker, and L. Zhu, , Phys. Rev. D **84** 055020 (2011) arXiv:hep-ph/1012.4460

1. Introduction

Motivation

- Evidence for the existence of DM

  WIMPs (Weakly Interacting Massive Particles): well-motivated DM candidate

  → Annihilation cross section of a pair of DM → $M \sim 100$ GeV (Weak scale)

- Many beyond-SM models (e.g., SUSY, UED, and Little Higgs) contain such a DM candidate.

  → direct/indirect measurement, collider experiment

  → (For most of them,) Z_2/parity as the DM stabilization symmetry

- Z_2 is **NOT** the only choice to stabilize DM!

  → Any discrete or continuous global symmetry can be employed to stabilize DM.

  → Should identify the nature of the symmetry, *experimentally*.

  → Any **DISTINGUISHABLE** features, in particular, between Z_2 and Z_3 in collider signals?

  (Z_3 as a simple non-Z_2: e.g., warped GUT: K. Agashe and G. Servant, Phys. Rev. Lett. 93, 231805(2004) arXiv:0403143, E. Ma, Phys. Lett. B 662, 49 (2008) arXiv:0708.3371, B. Batell, arXiv: 1007.0045)

  → **M_{T2} distribution as a tool**

1. Introduction

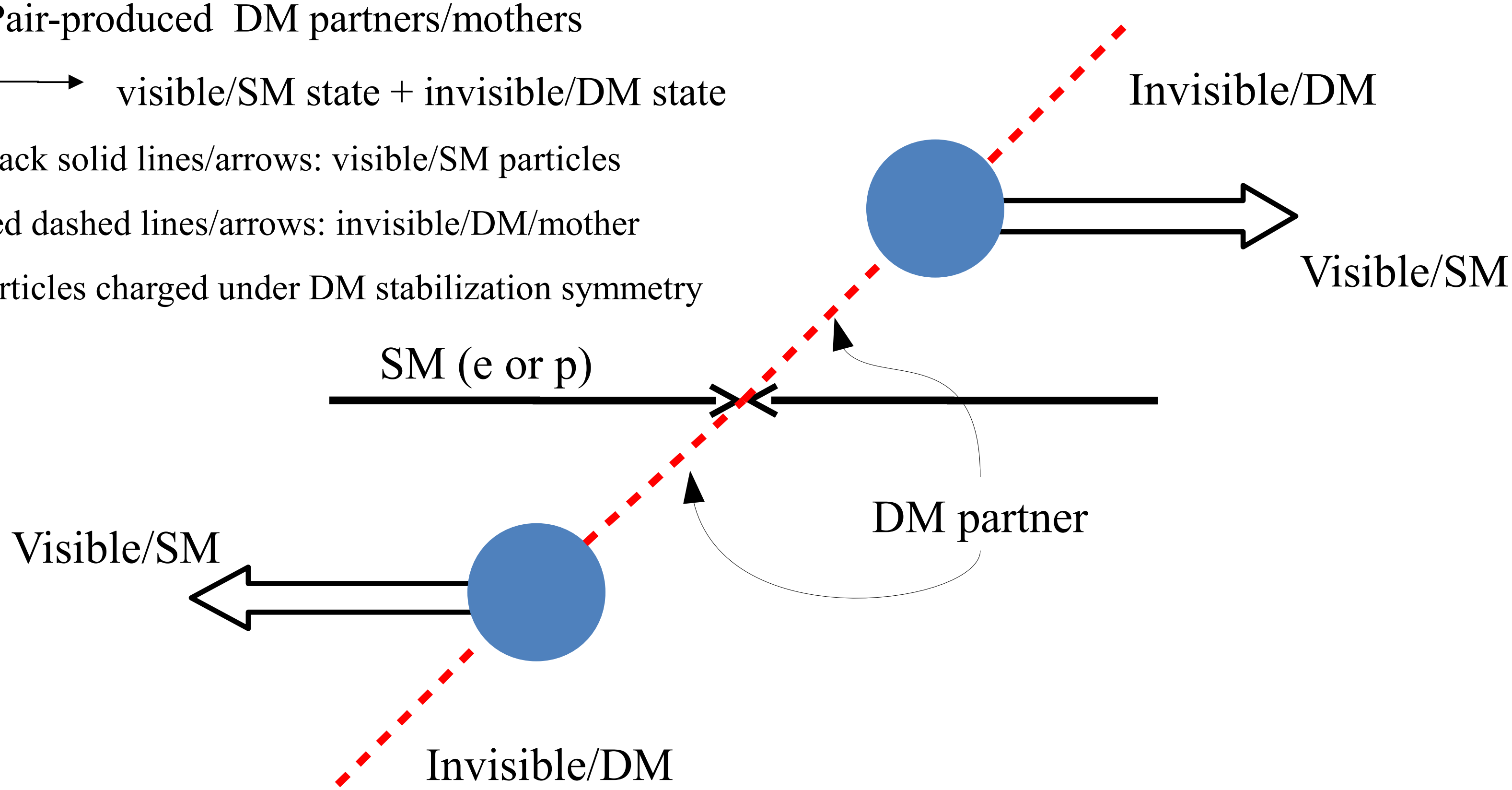
Collider signals

- Pair-produced DM partners/mothers

  ⟶ visible/SM state + invisible/DM state

Black solid lines/arrows: visible/SM particles

Red dashed lines/arrows: invisible/DM/mother particles charged under DM stabilization symmetry



2. Assumptions

Assumptions

- Model-independent argument (for any Z_3 models)

  → Possible to generalize to more complicated symmetries
- Pair-produced same mother particles
- Looking at the decay on **BOTH** decay sides assuming off-shell intermediate states.

  cf) one decay side using invariant mass variable → see Agashe, DK, Toharia, and Walker Phys. Rev. D **82** 015007 (2010) arXiv: hep-ph/1003.0899
- Mother particles decay into DM **INSIDE** the detector.

  → no meta-stable mother particles (See Walker arXiv:hep-ph/0907.3142)
- Massless visible/SM particles (just for simplicity)

3. Z_3 symmetry

Z_3 primer

$$\Phi \to \Phi \exp\left(\frac{2\pi i}{3} q\right) \qquad q = 0, +1, -1 (\equiv +2)$$

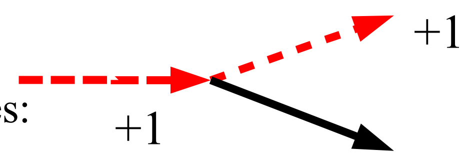
neutral charged (under Z_3)

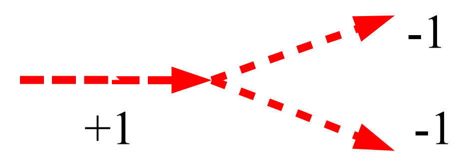
- DM is charged +1 ⟶ antiparticle -1 (= +2) $DM \neq \overline{DM}$

  (Under Z_2: DM +1 ⟶ antiparticle -1 (=+1) $DM = \overline{DM}$)

- DM is Dirac fermion or complex scalar.

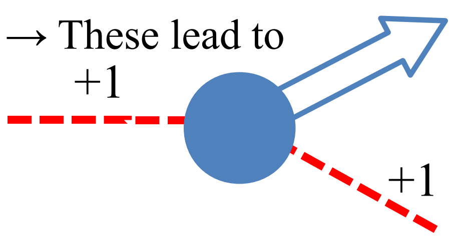
- Vertex with 2 Z_3- or 3 Z_3-charged particles:



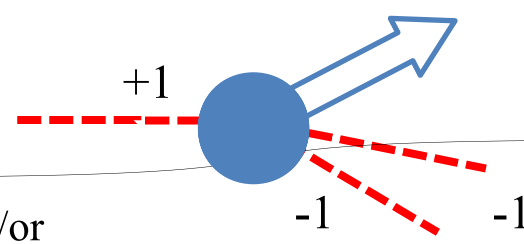


"charged-charged-charged" and "charged-charged-neutral"

→ These lead to



and/or



Anti-particles of each other (same mass)

4.1 Review on M_{T2} variable

Why M_{T2}?

- More information available from both decay sides

  cf) invariant mass variable of visible particles from the same decay side

- Single visible particle in each decay side: invariant mass variable does NOT work
- However, complicated: *invisible* particles in the final state (missing energy/momentum)

  → Missing energy/momentum shared by the two decay chains

  → M_{T2} constructed to comprehend this situation

- **Main strategy**

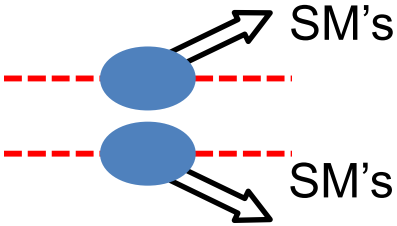
  → Investigate M_{T2} variable in Z_2 and Z_3 models

  → Find any observables/features different in Z_2 and Z_3 models

4.1 Review on M_{T2} variable

M_{T2} [1] primer

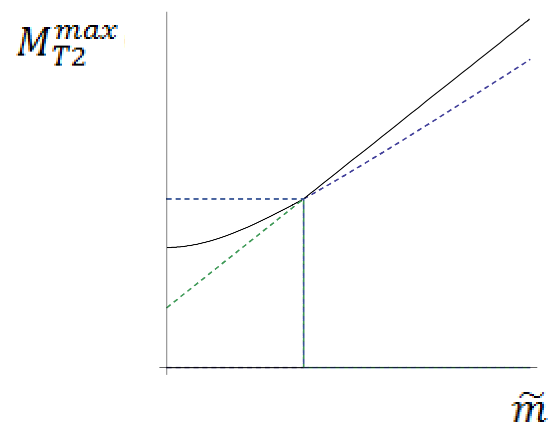
- M_{T2} variable: generalization of the transverse mass to the case where pair-produced mother particles decay into SM's & DM per mother



$$M_{T2}(\tilde{m}) = \min_{\vec{p}_T^{\,v(1)}+\vec{p}_T^{\,v(2)}+\vec{p}_T^{\,i(1)}\vec{p}_T^{\,i(2)}=0} [\max\{M_T^{(1)}, M_T^{(2)}\}]$$

- $M_{T2}^{max}(\tilde{m} = m_{DM}) = M$ ($\tilde{m}$: trial DM/LSP mass, M: mother mass)
- **Kink structure**[2] (for the case with more than one visible/SM particle in each decay chain) due to two types of solution (balanced/unbalanced)

  → **direct measurement of DM and mother mass**



1) C.G. Lester, D.J. Summers, Phys. Lett. B**463** , 99 (1999), arXiv:hep-ph/9906349

2) W.S. Cho, K. Choi, Y.G. Kim and C.B. Park, Phys. Rev. Lett. **100**, 171801 (2008), arXiv:0709.0288

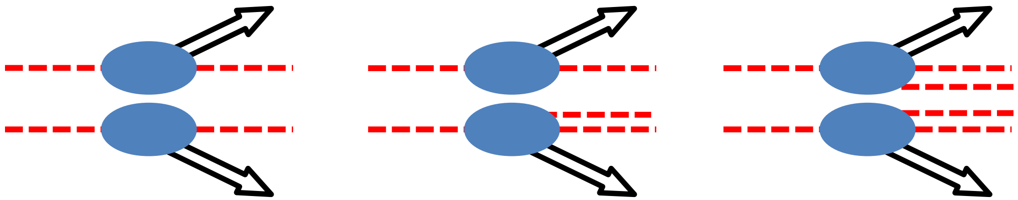
4.2 M_{T2} in Z_3 symmetry

"Naïve" M_{T2} method

- Each mother emits one or two DM: 2, 3, or 4 DM in the final state

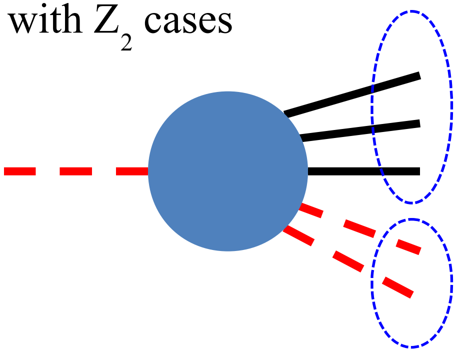
  (**E_2, E_3, and E_4** type events

  depending on # of DM)



- Still apply M_{T2} variable assuming only 1 DM in each decay chain → <u>"Naïve" M_{T2} method</u>
- Will provide different/contradictory and more features compared with Z_2 cases

Theoretical prediction on the upper edge



- Find the situation to yield the upper edge in M_{T2} distribution
- Consider the "effective" mass of invisible particles

  as well as the effective mass of visible particles in the sense of M_{T2} variable

4.2 M_{T2} in Z_3 symmetry

One visible/SM particle in each decay chain

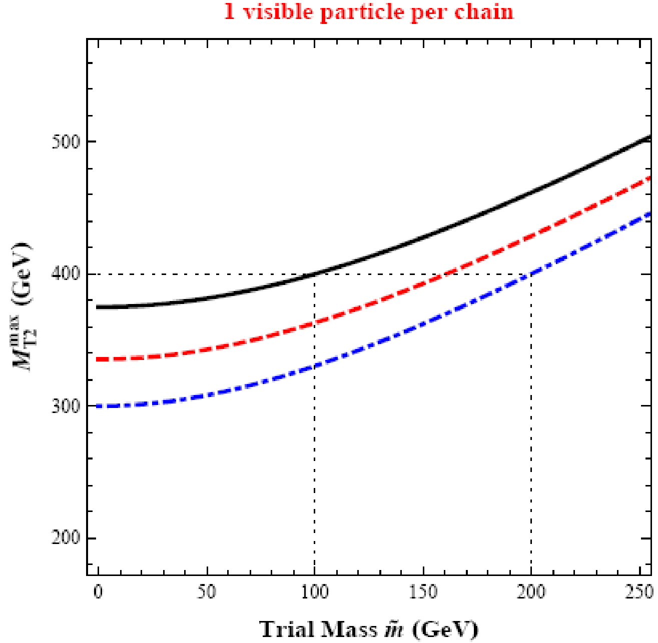
- No kink structure as expected
- Three different upper edges corresponding to three different types of events

$M^{max}_{T2,E_2} > M^{max}_{T2,E_3} > M^{max}_{T2,E_4}$ for all trial DM mass

$$M^{max}_{T2,E_2} = \sqrt{\frac{(M^2 - m^2_{DM})^2}{4M^2}} + \sqrt{\frac{(M^2 - m^2_{DM})^2}{4M^2} + \tilde{m}^2}$$

$$M^{max}_{T2,E_3} = \sqrt{\frac{(M^2 - m^2_{DM})(M^2 - 4m^2_{DM})}{4M^2}} + \sqrt{\frac{(M^2 - m^2_{DM})(M^2 - 4m^2_{DM})}{4M^2} + \tilde{m}^2}$$

$$M^{max}_{T2,E_4} = \sqrt{\frac{(M^2 - 4m^2_{DM})^2}{4M^2}} + \sqrt{\frac{(M^2 - 4m^2_{DM})^2}{4M^2} + \tilde{m}^2}$$



$M = 400GeV, m_{DM} = 100GeV$

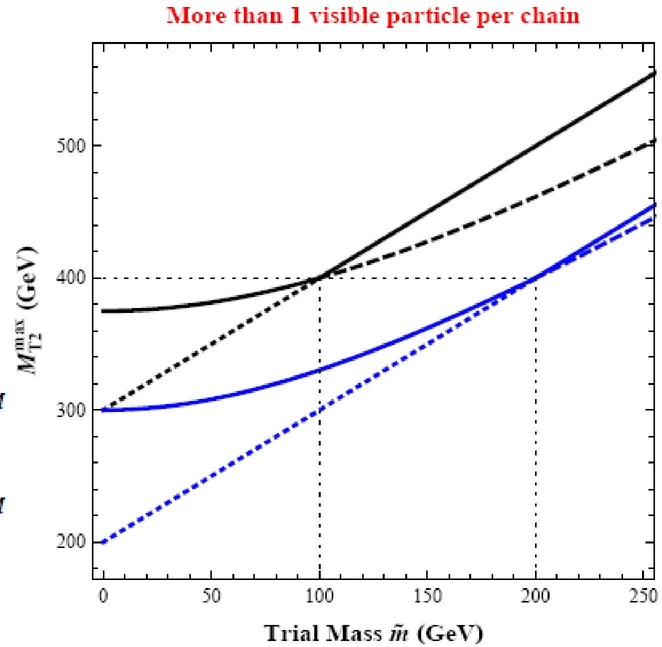
4.2 M_{T2} in Z_3 symmetry

More than one visible/SM particle in each decay chain

- Kink appears as expected, but not always for E_3
- Determine mother and DM masses by kink from E_2 type events, and cross check by the kink from E_4 type events

$$M_{T2,E_2}^{max} = \begin{cases} M - m_{DM} + \tilde{m}, & \tilde{m} \geq m_{DM} \\ \sqrt{\frac{(M^2 - m_{DM}^2)^2}{4M^2}} + \sqrt{\frac{(M^2 - m_{DM}^2)^2}{4M^2} + \tilde{m}^2}, & \tilde{m} \leq m_{DM} \end{cases}$$

$$M_{T2,E_4}^{max} = \begin{cases} M - 2m_{DM} + \tilde{m}, & \tilde{m} \geq 2m_{DM} \\ \sqrt{\frac{(M^2 - 4m_{DM}^2)^2}{4M^2}} + \sqrt{\frac{(M^2 - 4m_{DM}^2)^2}{4M^2} + \tilde{m}^2}, & \tilde{m} \leq 2m_{DM} \end{cases}$$



$M = 400GeV, m_{DM} = 100GeV$

4.2 M_{T2} in Z_3 symmetry

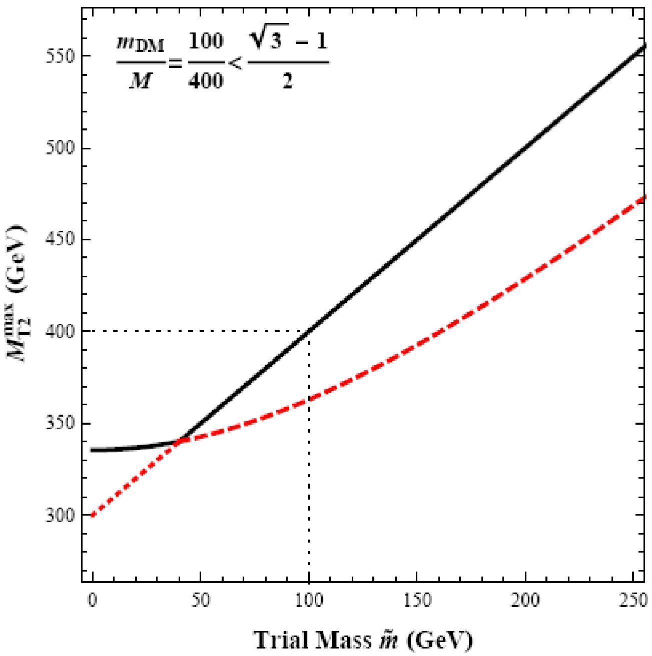
E_3 type events under M_{T2}

- Asymmetric in the final states of both decay sides
- Kink appears depending on the mass hierarchy between mother and DM masses

$$M^{max}_{T2,E_3} = M - m_{DM} + \tilde{m} \quad \text{for all } \tilde{m}$$

$$M^{max}_{T2,E_3} = \begin{cases} M - m_{DM} + \tilde{m} \quad , & \tilde{m} \geq m' \\ \sqrt{\dfrac{(M^2 - m^2_{DM})(M^2 - 4m^2_{DM})}{4M^2}} + \\ \sqrt{\dfrac{(M^2 - m^2_{DM})(M^2 - 4m^2_{DM})}{4M^2} + \tilde{m}^2}, & \tilde{m} \leq m' \end{cases}$$

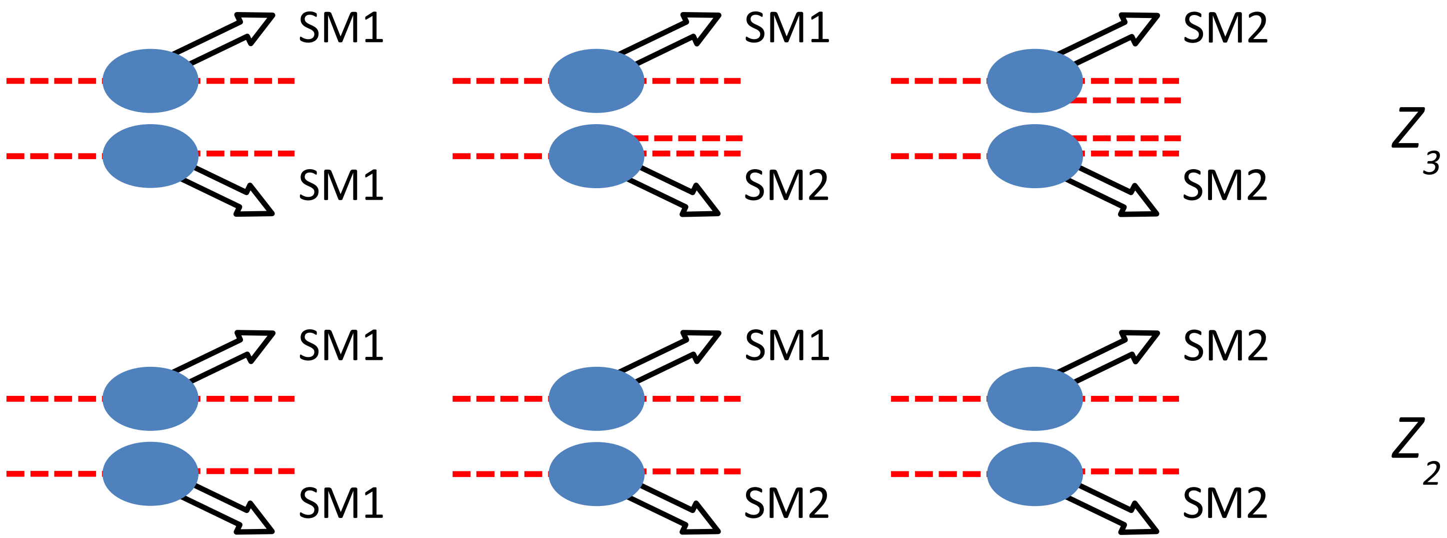
$$m' = \frac{(M - m_{DM})(\sqrt{(M^2 - m^2_{DM})(M^2 - 4m^2_{DM})} - M(M - m_{DM})}{2M(M - m_{DM}) - \sqrt{(M^2 - m^2_{DM})(M^2 - 4m^2_{DM})}}$$



4.3 Non-identical visible particle(s) in 2 decay chains

3 decay topologies

- SM state with 1 DM is different from SM state with 2DM



- Main idea: **Three different types of event/richer structures** in the sense of M_{T2} variable

4.3 Non-identical visible particle(s) in 2 decay chains

One visible/SM particle in each decay chain

- Z_2 case: Only one common upper edge (1DM + 1DM only)
- Z_3 case: Three different upper edges in M_{T2} distribution (1 DM + 1DM, 1DM + 2DM, 2DM + 2DM) → Two of them for separate measurement of mother and DM masses, remaining one for cross-check in spite of a kink
-

More than 1 visible/SM particle in each decay chain

- Z_2 case: Only one upper edge, and a kink structure at (trial m_{DM}) = (real m_{DM})
- Z_3 case: 2 edges for (trial m_{DM}) ≥ (real m_{DM}), 3 edges for (trial m_{DM}) < (real m_{DM}), and also kink structure in each type of events → Measurement of mother and DM masses from (1DM +1DM) give predictions on upper edges & kink location for the other two types of events

4.4 Identical visible particle(s) in 2 decay chains

Possible trials

- No way to separate E_2, E_3, and E_4 simply by particle identities → Only combined distribution
- 1 visible particle in each decay chain: Kinks in M_{T2} distribution at the upper edges for E_3, E_4?

  → Not clear due to longer tails

  → Smearing effect/Statistical fluctuations
- More than 1 visible particle in each decay chain:

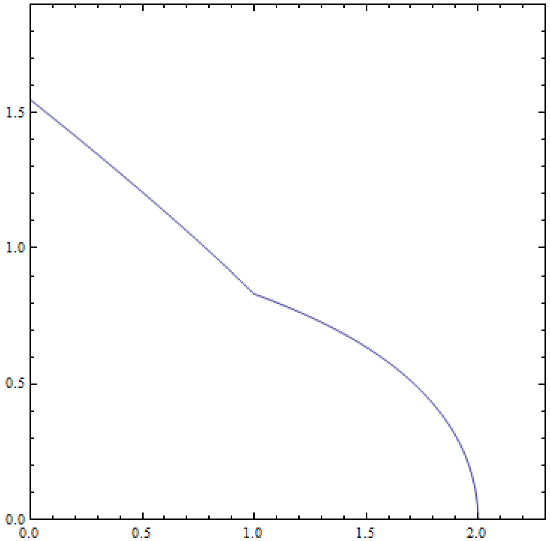
  → Still hard to see this kink

⟹ **Introduction of a new method**

→ Separate E_3 events from combined events

(using imbalance of E_3 type events in both decay sides)

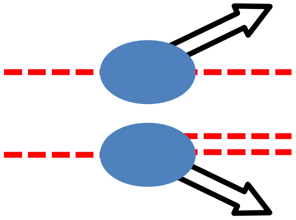
→ Do the same analysis for the separated events



4.4 Identical visible particle(s) in 2 decay chains

Pt/Ht ratio cut

- Employ the fact that E_3 type events are asymmetric in the final state while E_2 are symmetric: 2DM side carries less momentum/energy than 1DM side, on average
- Define P_t/H_t ratio



$$R_{Pt} = \frac{P_t^{max}}{P_t^{min}} \qquad R_{Ht} = \frac{H_t^{max}}{H_t^{min}}$$

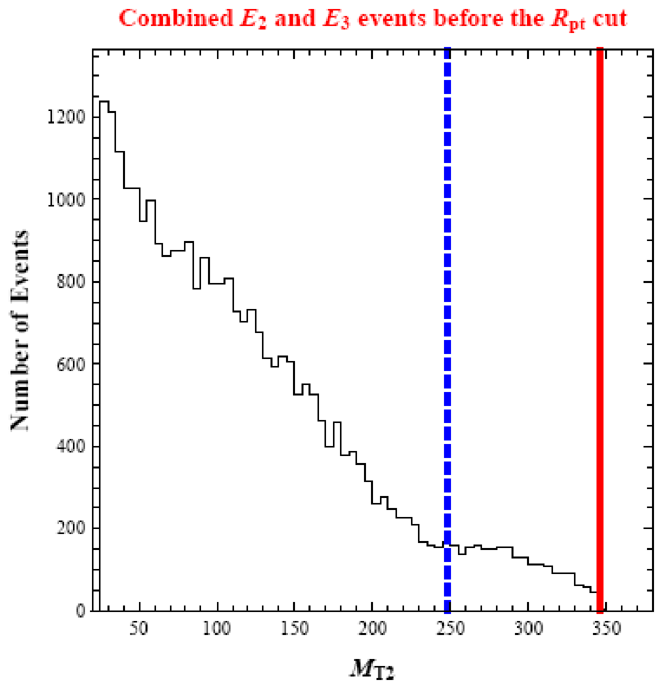
- Expect many E_2 type events give 1 vs. many E_3 type events give >1
- Remove/keep decay events by imposing ratio cuts
- Compare survival rates among different types of events
- Re-do M_{T2} analysis after cuts as further confirmation: for Z_3 upper edge will shift down (especially, to distinguish Z_3 from Z_2 + neutrino)

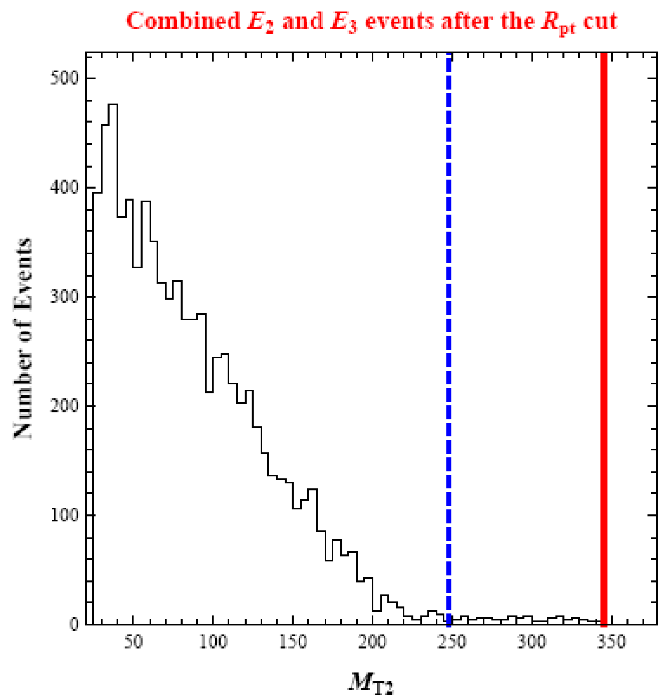
4.4 Identical visible particle(s) in 2 decay chains

One visible/SM particle in each decay chain

- Solid red – theoretical E_2 edge, dotted blue – theoretical E_3 edge

$M = 400GeV, m_{DM} = 150GeV, \tilde{m} = 25GeV$ R_{Pt} cut = 5 $E_2 : E_3 = 1:2$





4.4 Identical visible particle(s) in 2 decay chains

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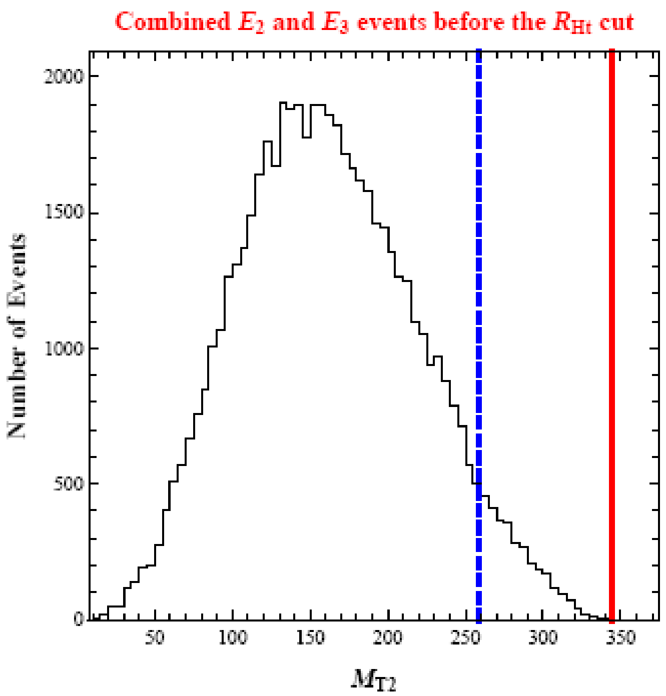
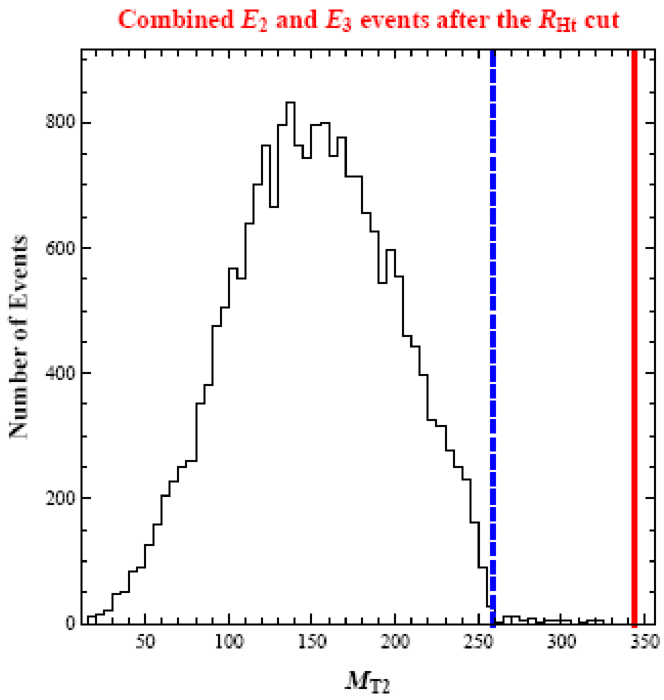




5. Summary

We have learned that…

- DM stabilization symmetry does **NOT** have to be Z_2

↓

- Mother particle decays in Z_3 → More structure → Can be distinguished from Z_2

↓

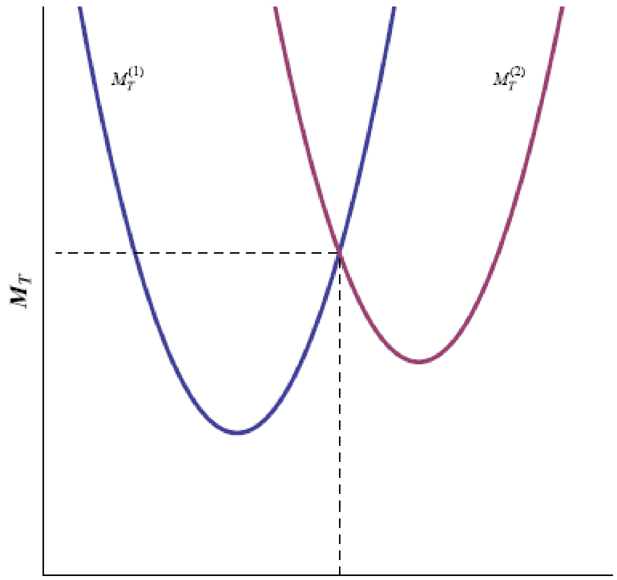
- 2,3, and 4 DM in the final state for Z_3 while 2 DM for Z_2
- Non-identical visible particle(s) : **NUMBER of UPPER EDGES in M_{T2}** from multiple decay topologies/M_{T2} distributions in Z_3
- Identical visible particle(s): event separation by **Pt/Ht RATIO CUT** → number of upper edges
- **A follow-up paper will come out soon. Stay tuned!**

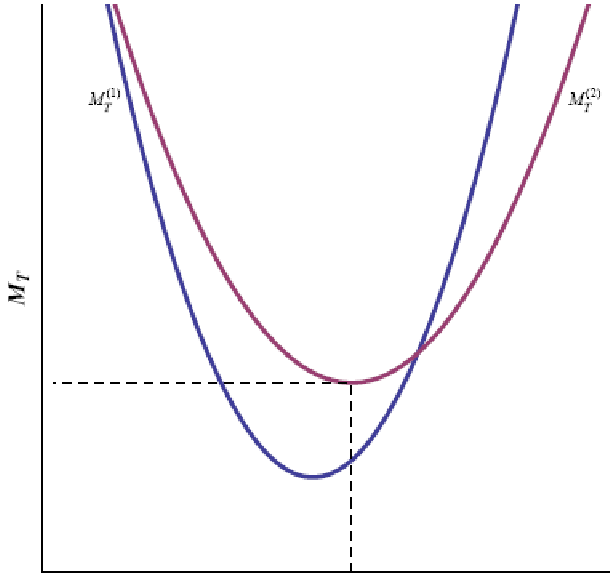
Thank You

Backup

M_{T2} primer: balanced and unbalanced solutions

- Balanced solution: intersection between two M_T's = M_{T2}
- Unbalanced solution: intersection between two M_T's > M_{T2}



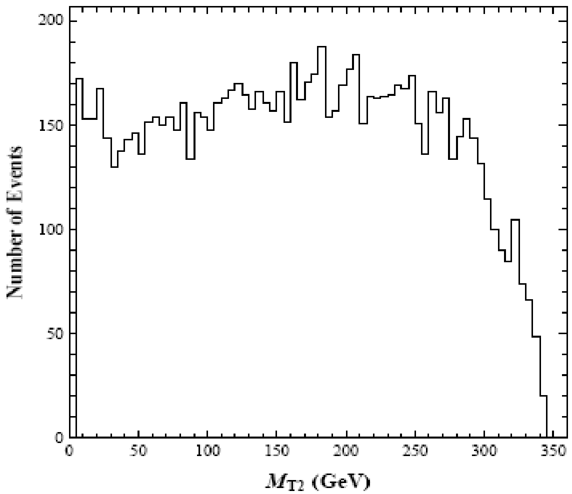


Backup

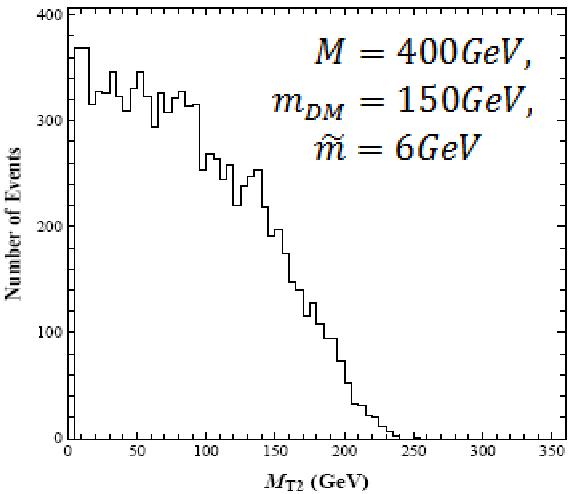
Shapes of M_{T2} distribution

- (Relatively) longer tail for E_3 and E_4 type events: more physical constraints (e.g. rapidity) between decay products should be satisfied
- Adding neutrino → relatively longer tail than pure E_2, but still distinguishable!

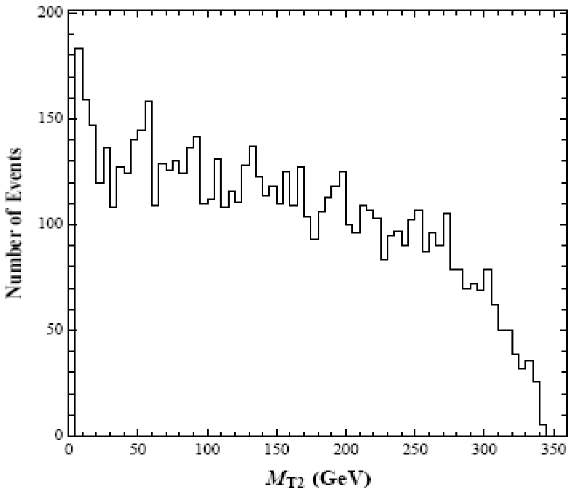
→ <u>E_2 and E_2+nu with same edges in Z_2 vs. E_2, E_3, and E_4 with different edges in Z_3</u>



E2 events



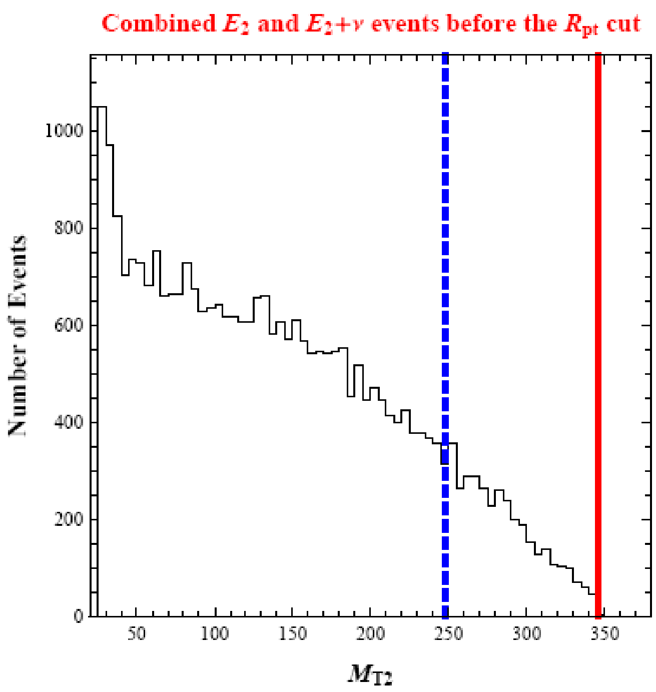
E3 events

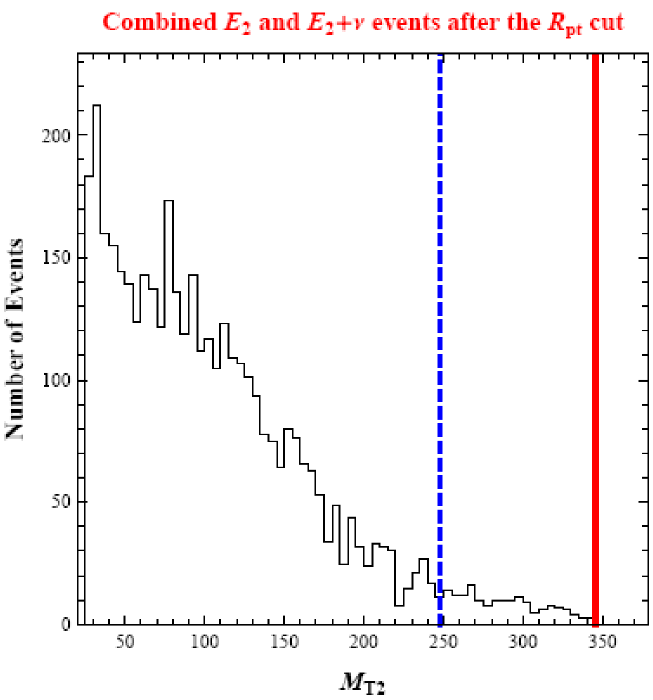


E2 + nu events

Backup

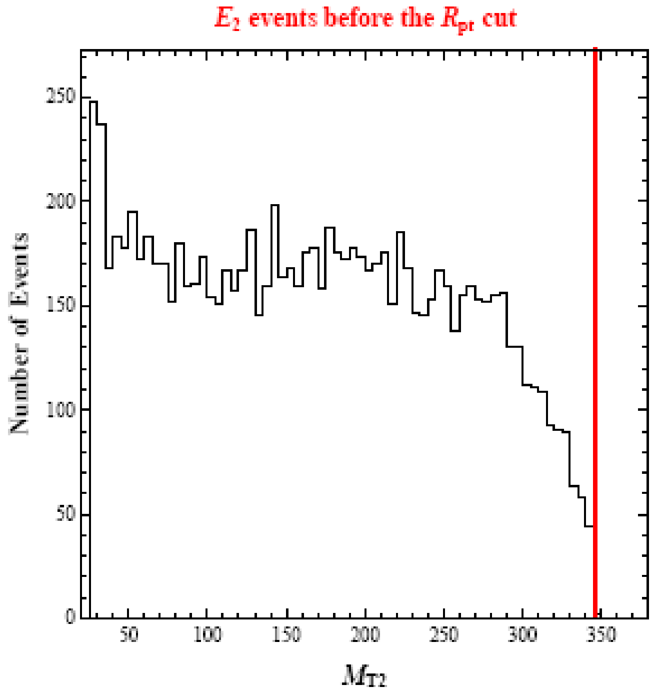
One visible/SM particle in each decay chain (E_2+nu)

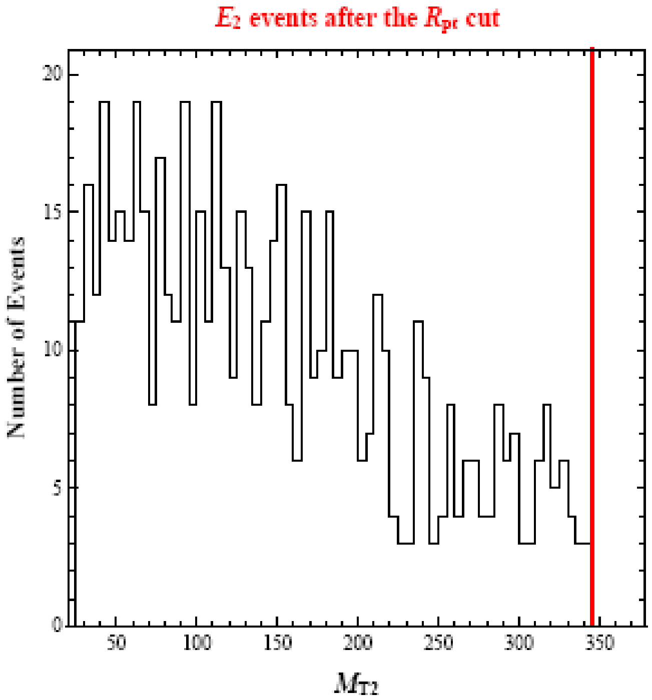




Backup

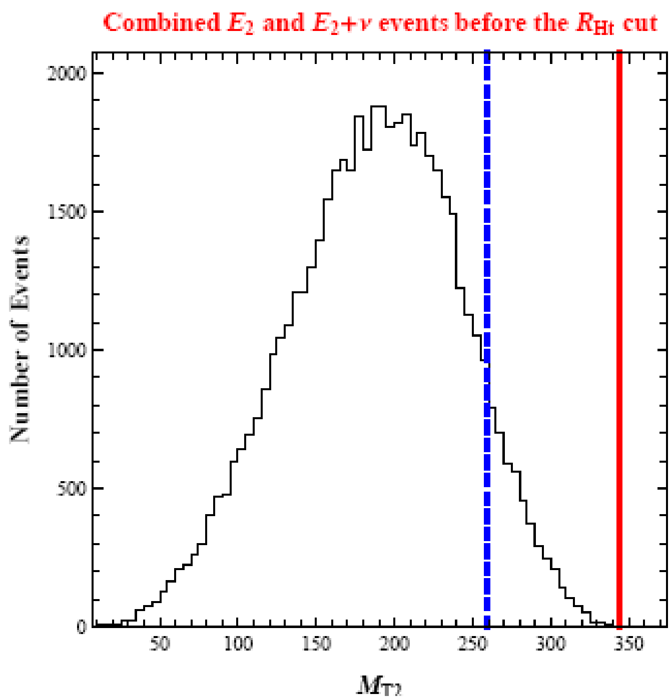
One visible/SM particle in each decay chain (E_2)

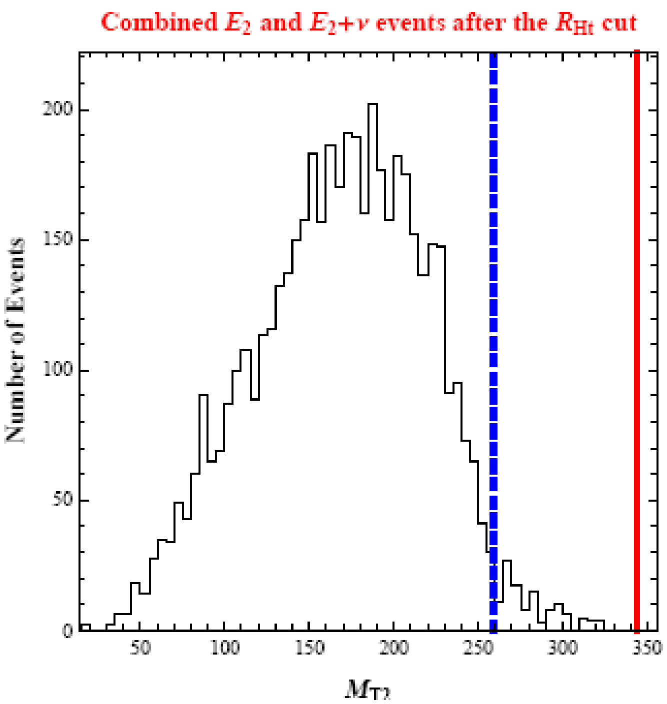




Backup

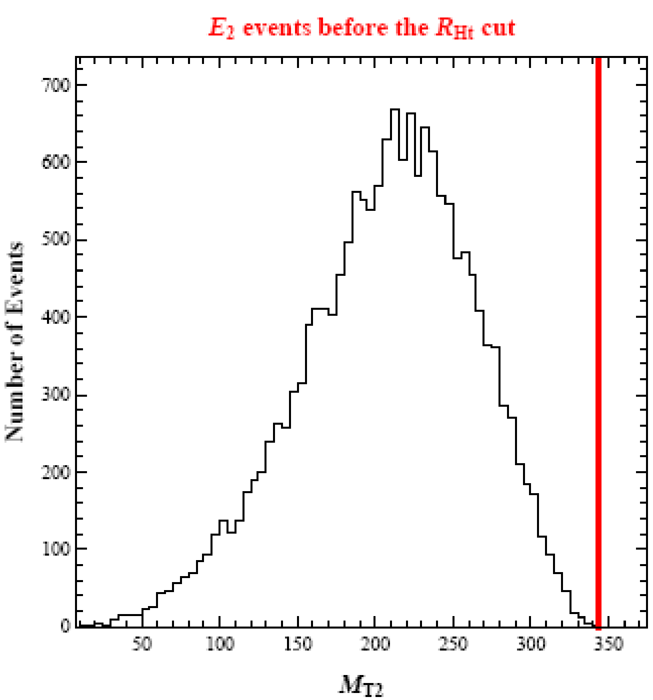
- **More than one visible/SM particle in each decay chain (E_2+nu)**

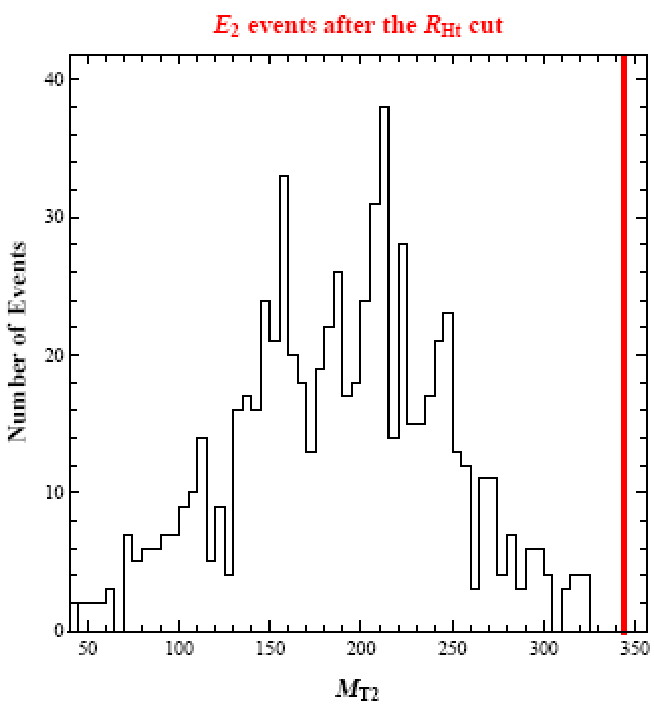




Backup

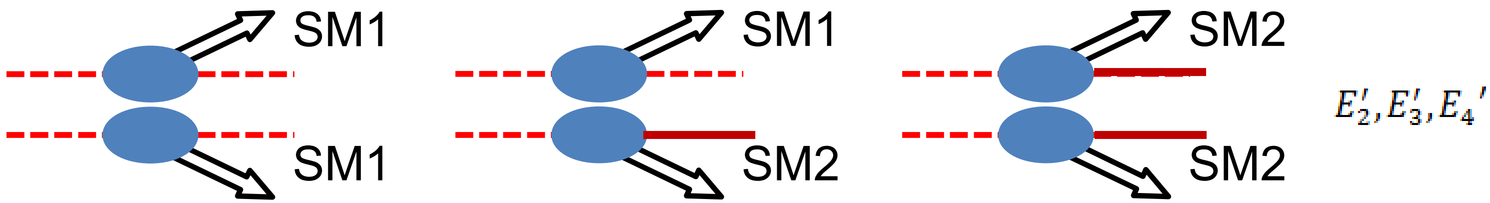
- **More than one visible/SM particle in each decay chain (E_2)**





Backup

Signal fakes

- (Effective) second invisible particle (e.g. another DM, collider-stable invisible, on-shell intermediate particle whose decay products are all invisible)
- 

- Three upper edges in M_{T2} distribution **NOT because of # of DM BUT because of another DM-like particle** → Can be resolved!

  → One SM/visible in each decay chain: **SHAPE** (3 clear sharp upper edges vs. 1 sharp edge + 2 (relatively) longer tailed edges

  → More than 1 SM/visible in each decay chain: 1) mother and DM masses from kink in M_{T2}^{max} vs. trial m_{DM} 2) Predictions on upper edges of E_3, E_4 3) Good matches only for Z_3

Backup

Signal fakes

- E_2', E_3', and E_4' type events are combined
- One visible particle in each decay chain

  → Two sharp kinks in the middle of the distribution: E_3' and E_4' have only 1 DM in each decay chain

- More than 1 SM/visible in each decay chain

  → 1) mother and DM masses from kink in M_{T2}^{max} vs. trial m_{DM} 2) Predictions on upper edges for the other types of events 3) Event separation by Pt/Ht ratio cut 4) Good matches only for Z_3