Searches for New Physics with M_2 Variables

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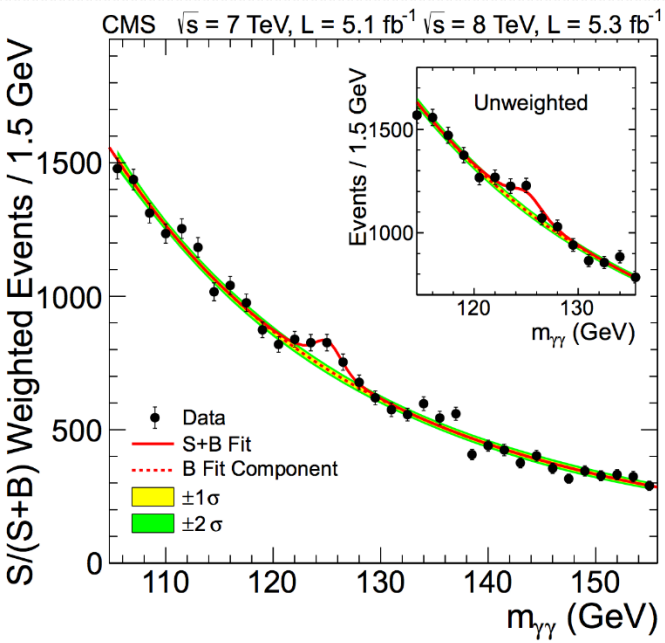
University of Florida, Gainesville
TRIUMF Theory Workshop, Vancouver, B.C., Canada, Sep 2014

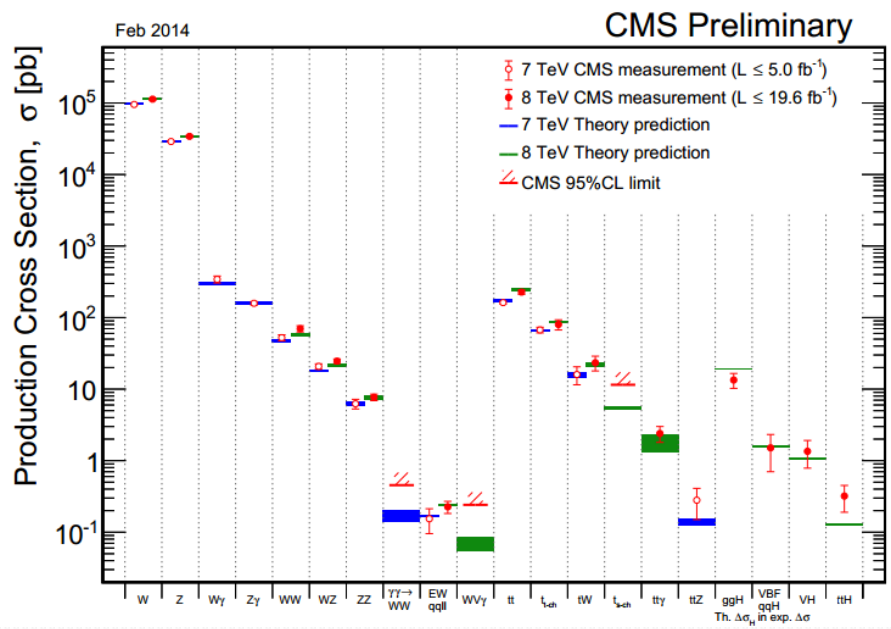
W.S.Cho, J.Gainer, DK, K.T.Matchev, F.Moortgat, L.Pape, and M.Park, JHEP 1408 (2014) 070, arXiv:hep-ph/1401.1449
W.S.Cho, J.Gainer, DK, K.T.Matchev, F.Moortgat, L.Pape, and M.Park ,
"Improving the sensitivity of stop searches with on-shell constrained invariant mass variables",work in progress
DK, H.S.Lee, and M.Park, "Search for dark Z' with on-shell constrained invariant mass variables", work in progress

1. Introduction

LHC Run I (7/8 TeV)

- Higgs discovery, SM precision measurement





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LHC Run II (13/14 TeV)

- Expecting new physics/BSM?
  - ✓ Supersymmetry, Extra dimension, or else?

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  - ✓ Better understanding of Higgs mass, i.e., hierarchy problem

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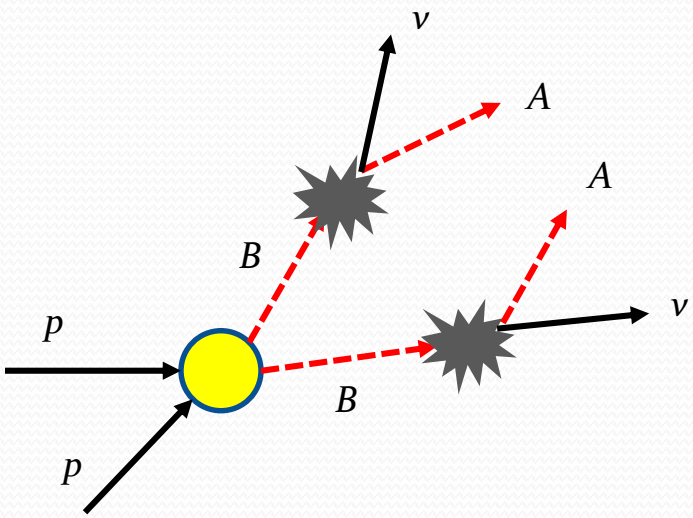
More sensitive strategies required!

Contents

2. M_2 variables

Review: M_{T2} variable

- Stransverse mass (M_{T2}): a generalization of the transverse mass to the case where pair-produced mother particles decay into two decay chains, each of which has visible particle(s) along with missing particle(s). [C.G. Lester, D.J. Summers (1999); A.J. Barr, C.G. Lester, M.A. Parker, B.C. Allanach, and P. Richardson (2002); A. Barr, C. Lester, and P. Stephens (2003)]



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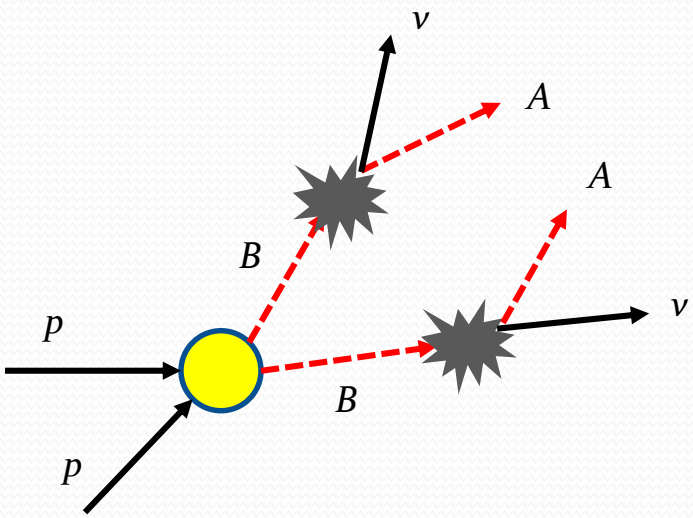
$$M_{T2}(\tilde{m}) = \min_{\vec{p}_T^{\,v(1)}+\vec{p}_T^{\,v(2)}+\vec{p}_T^{\,i(1)}\vec{p}_T^{\,i(2)}=0} [\max\{M_T^{(1)}, M_T^{(2)}\}]$$



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Key features of M_{T2} variable

- Distribution bounded above: kinematic endpoint in terms of mass parameters
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- When evaluating each M_{T2}, hypothesized(trial) DM mass imposed
  - ✓ Kink structure of maximum M_{T2} vs. trial mass → mass measurement [W.S. Cho, K. Choi, Y.G. Kim and C.B. Park (2007)]

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- (Typically) numerical minimization required
  - ✓ M_{T2} value
  - ✓ Ansatz for the **transverse** momentum of invisible particles obtained

2. M_2 variables

M_2 variable: Definition

- Two ways of understanding the M_2 variables

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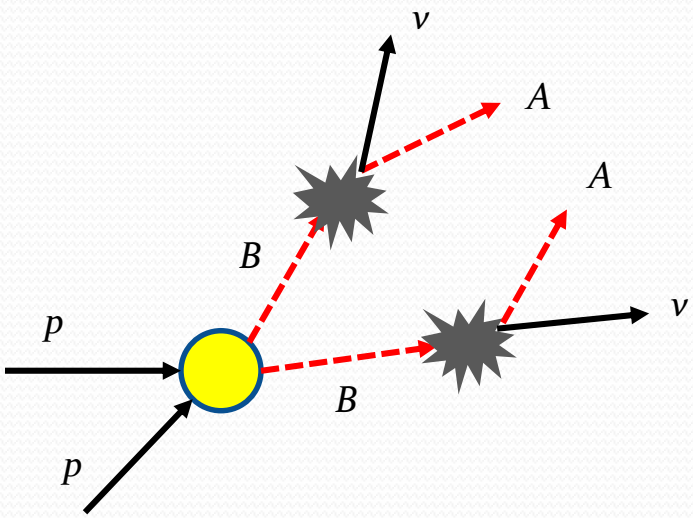
  i. (3+1) dimensional analogue of the (2+1) dimensional M_{T2} variable

  ii. Invariant mass including invisible parts for the pair-produced mother particles



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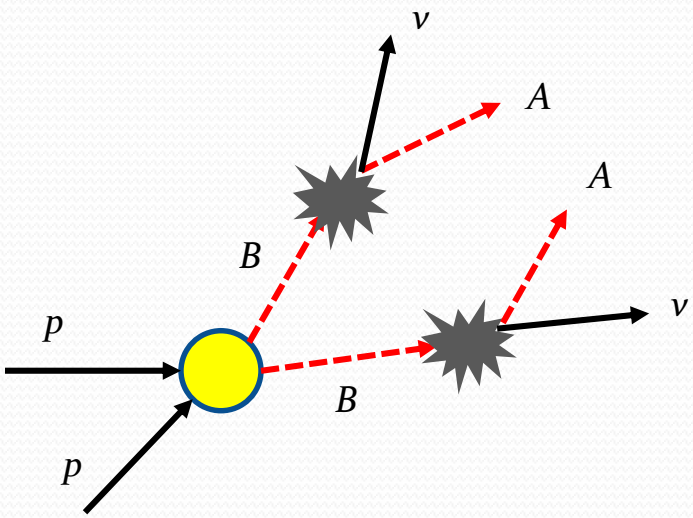

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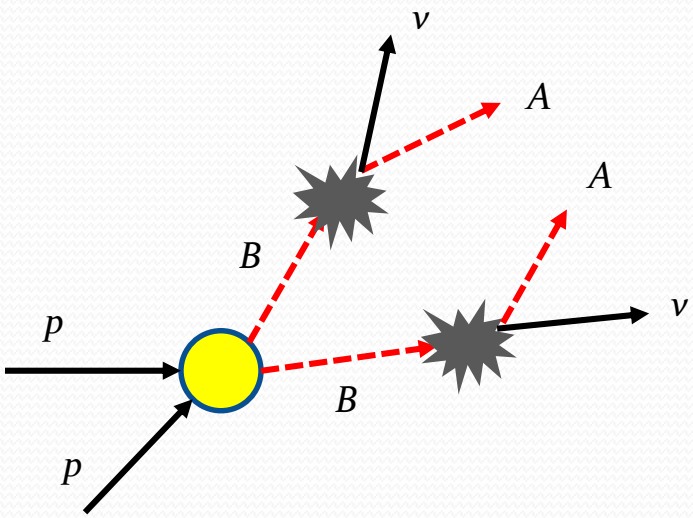
- Required constraint: MET condition (linear)
- Optional constraints: equal mass condition (explained shortly)



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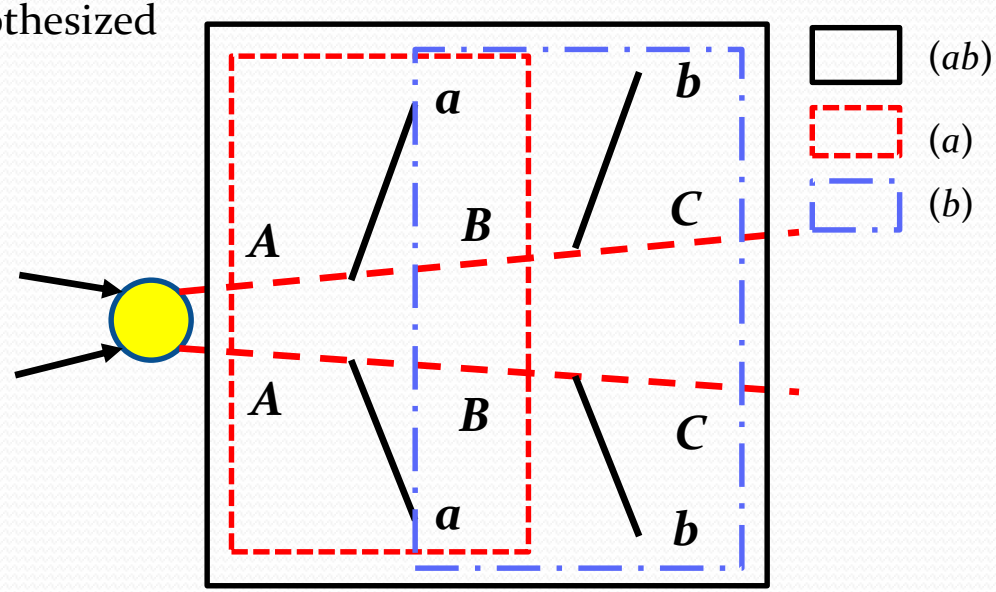
Model process and notations

- Di-leptonic ttbar-like event topology
  - ✓ Three sub-systems: (ab), (a), and (b) subsystems
  - ✓ Parent (P): particle whose mass minimized
  - ✓ Daughter: particle whose mass hypothesized
  - ✓ Relative (R): the other particle



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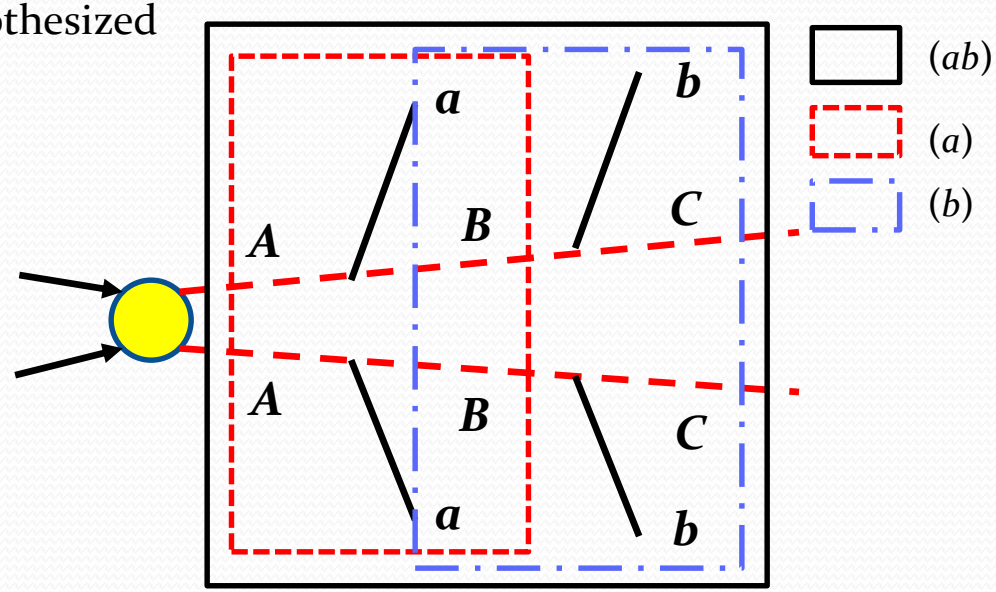
- Two more possible constraints:

$$M_{P_1}^2 = M_{P_2}^2 \text{ or } M_{R_1}^2 = M_{R_2}^2$$



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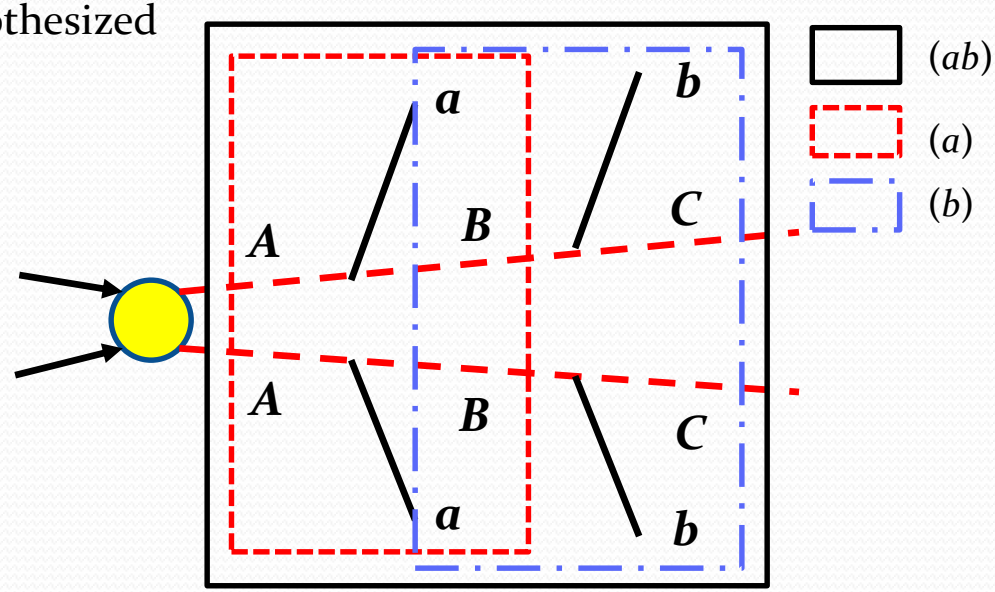
- C (X): constrained (unconstrained)
  - M_{2XX}, M_{2CX}, M_{2XC}, M_{2CC}



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- Non-linearly constrained minimization procedure required.
  - ✓ Code available:

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  - ✓ M_2 value
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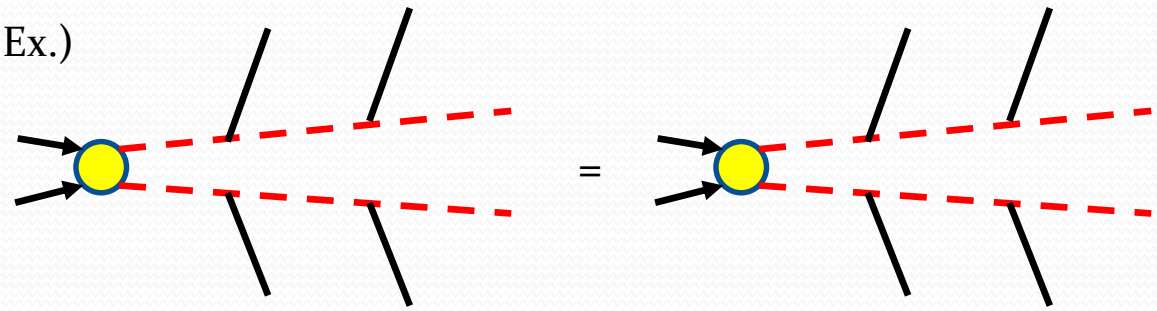
  - ✓ Possible to reconstruct the mass of the relative particles

3. Key properties

Property 1: Enhancement of endpoint structure

- If model assumption = actual physics

Ex.)



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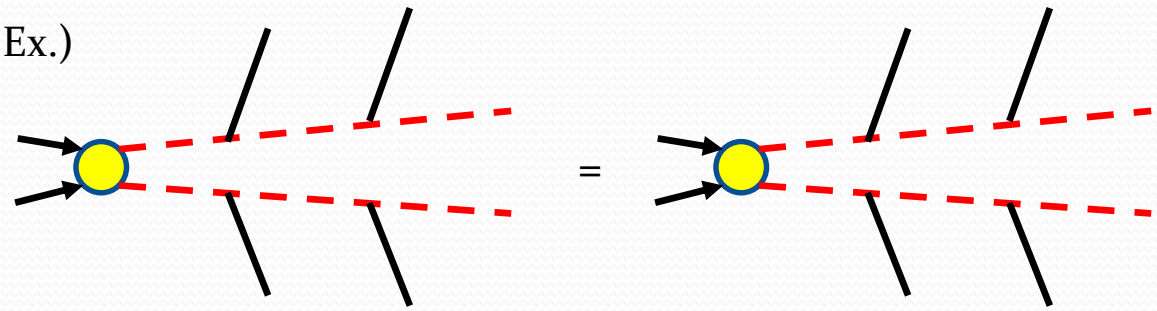

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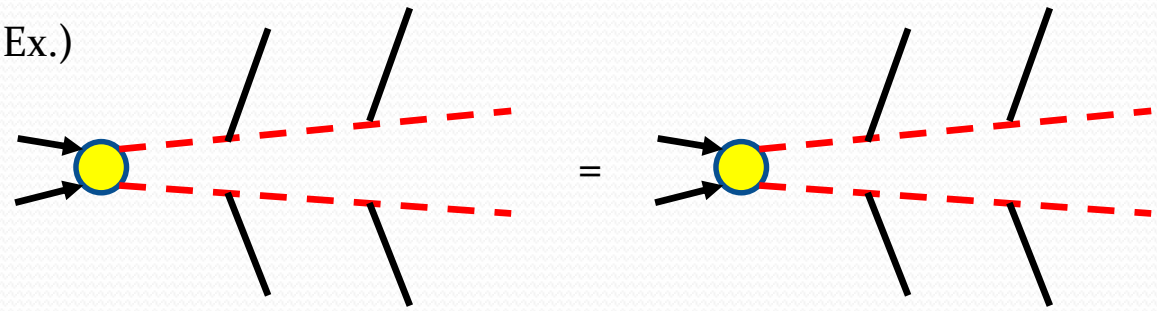

- Events more populated towards endpoints as more constraints imposed
  - ✓ Mathematically, $M_{T2} = M_{2XX} = M_{2CX} \leq M_{2XC} \leq M_{2CC}$

$$M_{T2}^{max} = M_{2XX}^{max} = M_{2CX}^{max} = M_{2XC}^{max} = M_{2CC}^{max}$$

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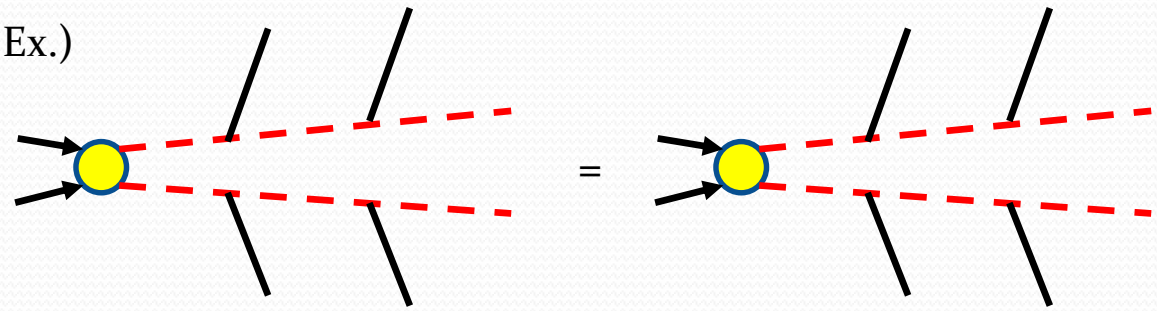

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    $$M_{T2}^{max} = M_{2XX}^{max} = M_{2CX}^{max} = M_{2XC}^{max} = M_{2CC}^{max}$$
  - ✓ Heuristically/intuitively, **better chance to find the true solution** due to same constraints as the actual event

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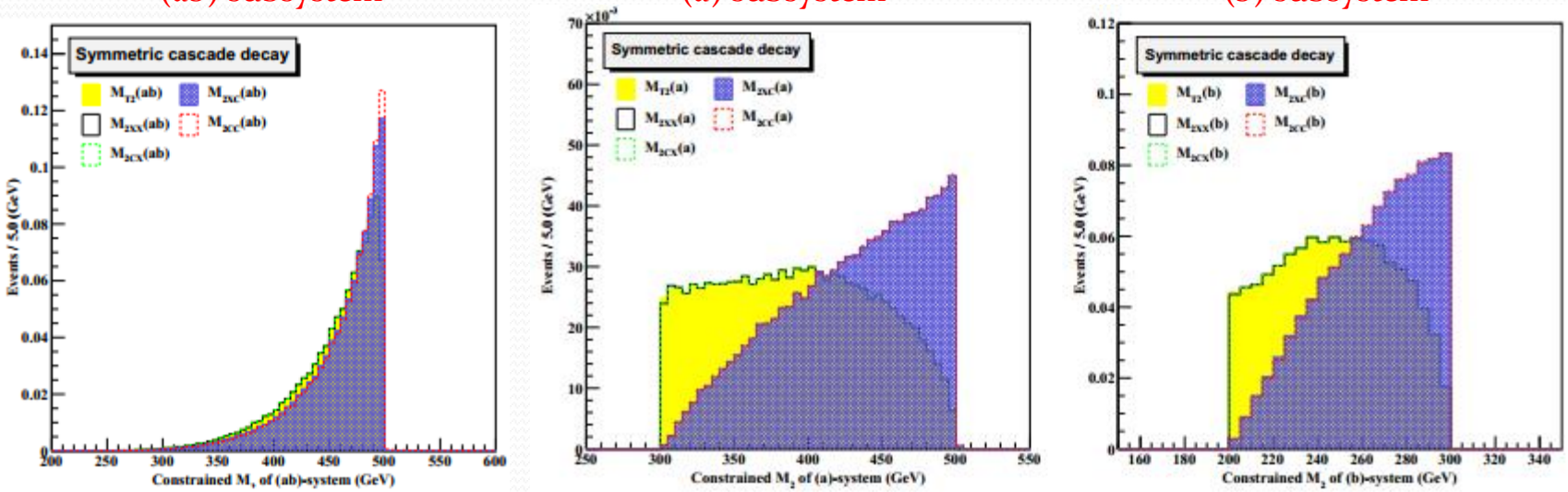
Property 1: Enhancement of endpoint structure

- Mass spectrum: (500, 300, 200) GeV
- Test mass = true mass

(*ab*) subsystem (*a*) subsystem (*b*) subsystem



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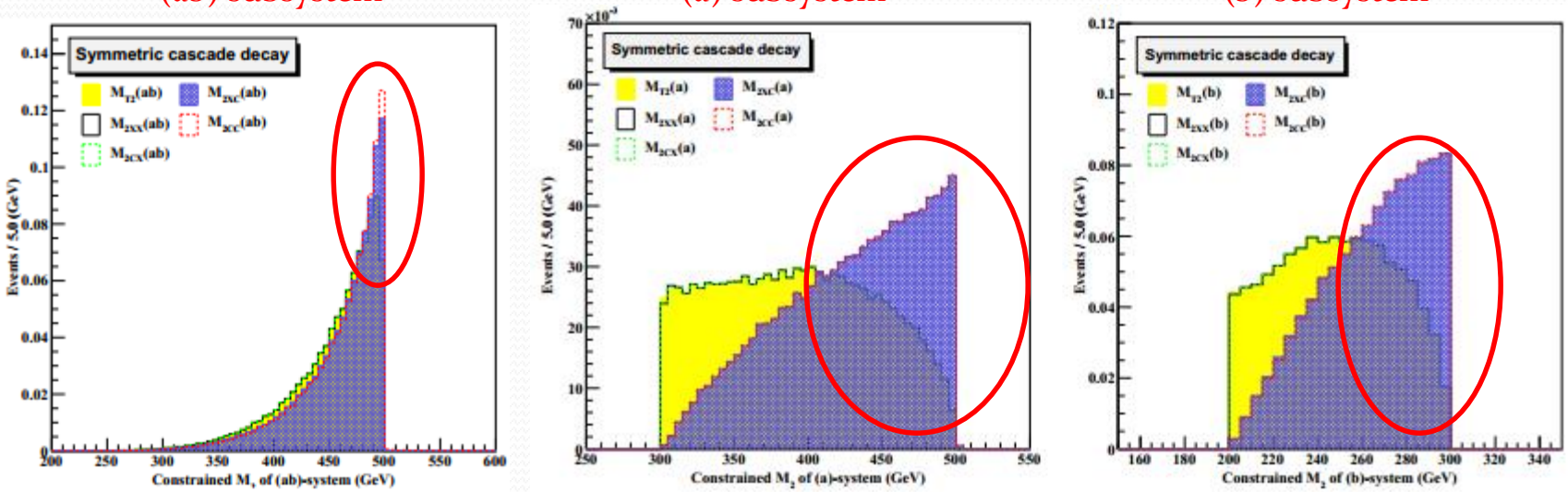

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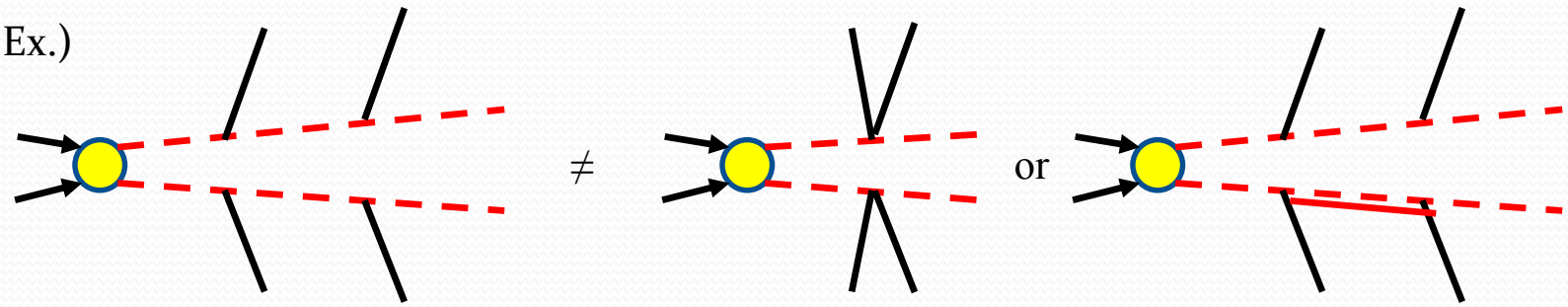

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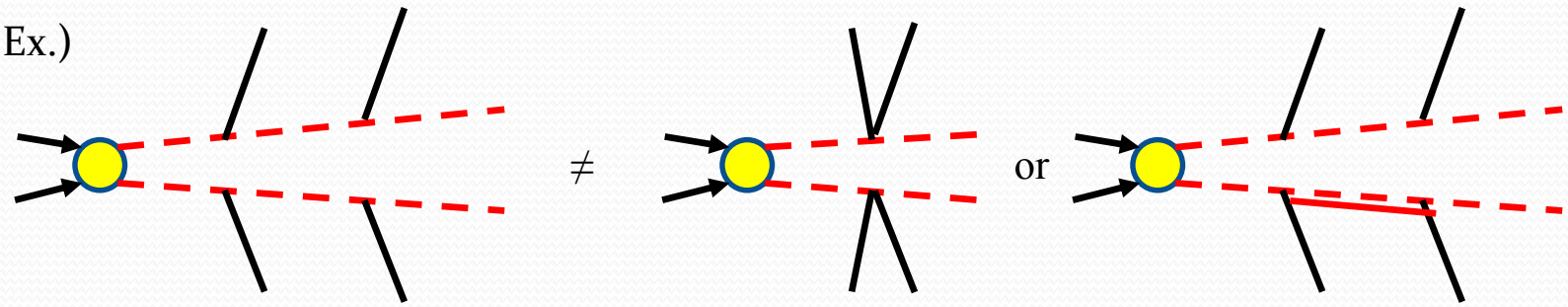

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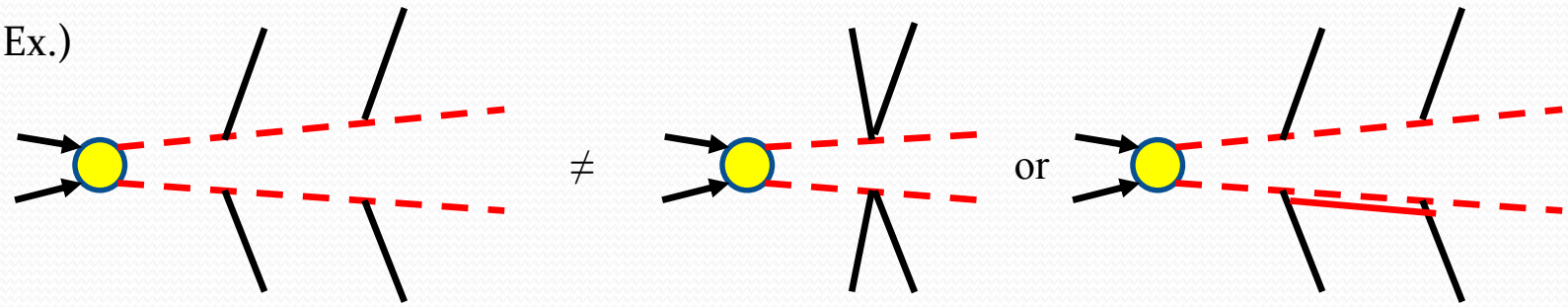

- Two model assumptions for (*ab*) subsystem (as an example)
  - ✓ Existence of an intermediate resonance in each decay side
  - ✓ Same mass for the two intermediate states
- Inconsistency with model assumptions → M_{2XC}, M_{2CC} lost its physical meaning → Possible to have events **violating the expected endpoint**

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Property 2: Endpoint violation

- Mass spectrum: (500, 300, 200) GeV, (500, 200) GeV, (500, 400 or 300, 200) GeV
- *(ab)* subsystem considered: test mass = 200 GeV

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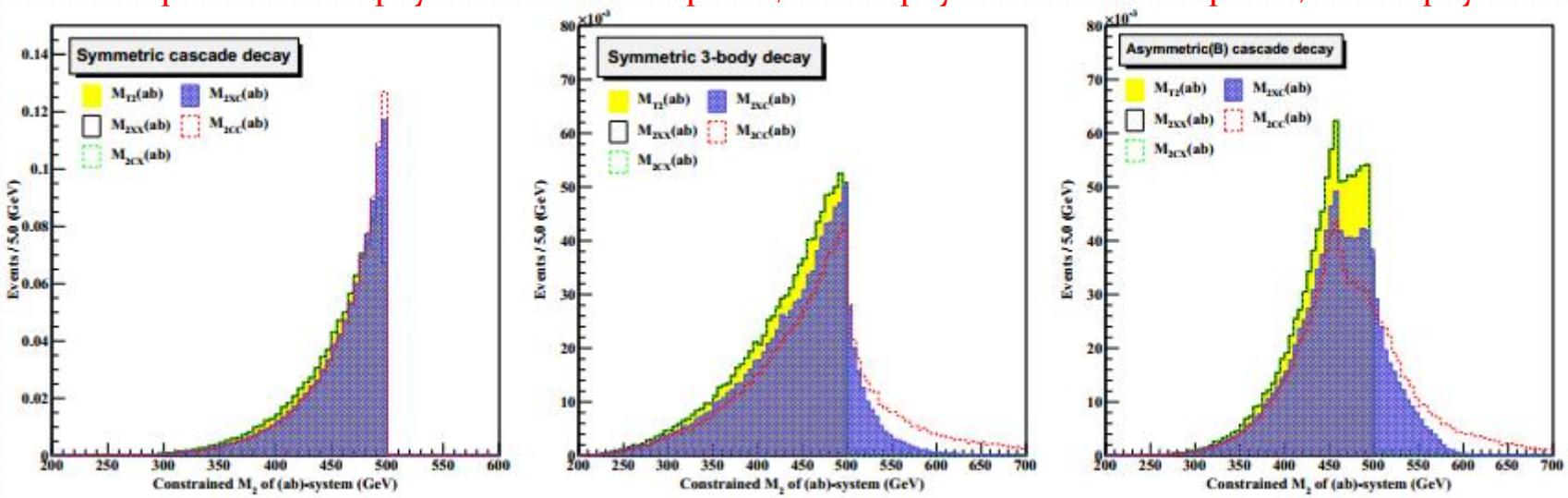

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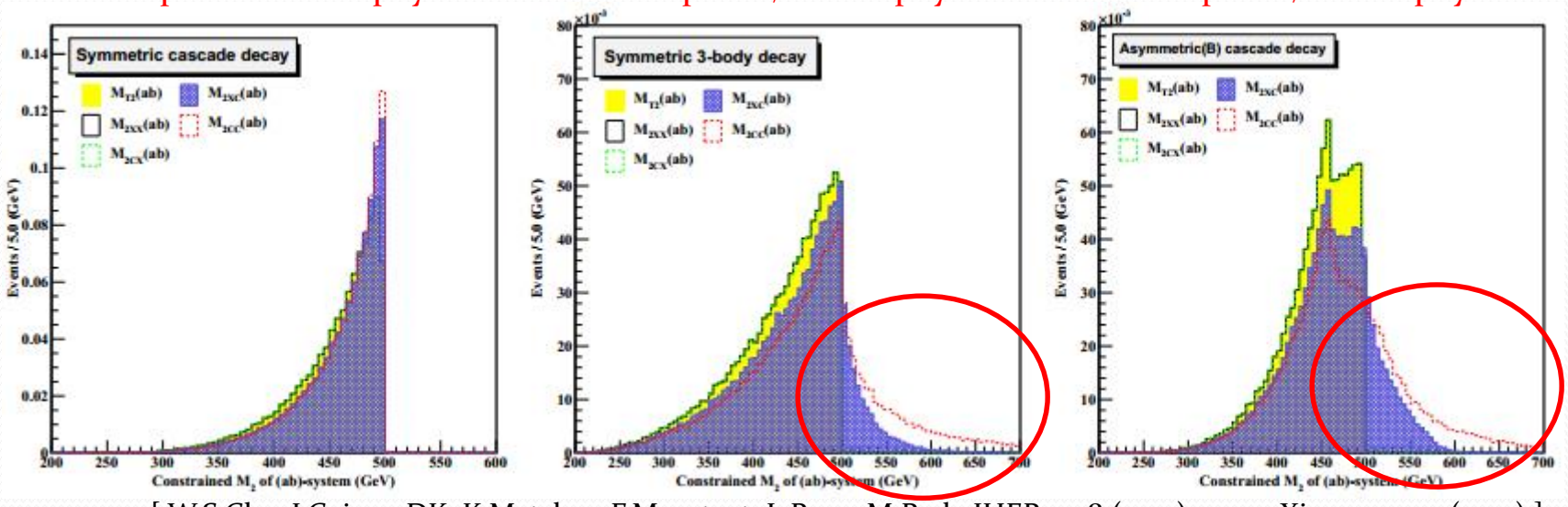

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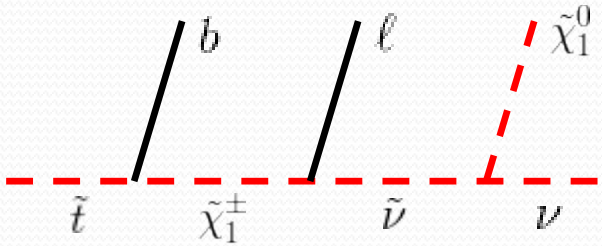
4. New physics search strategies

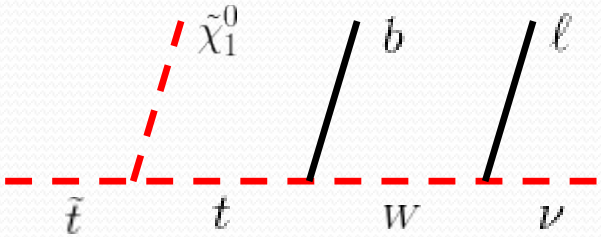
Stop search

- Signal processes

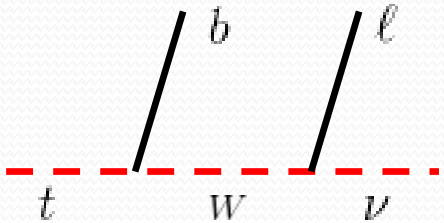
(a) Topology 1



(b) Topology 2



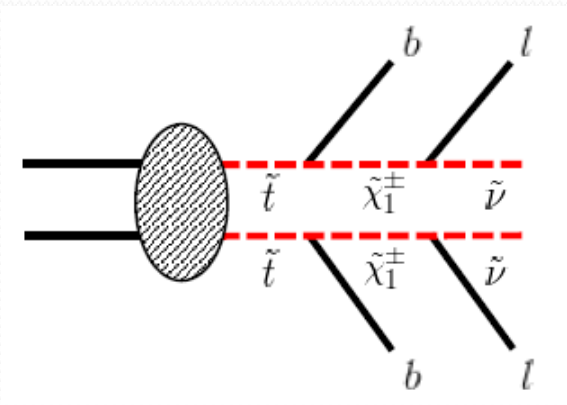
- Major background process

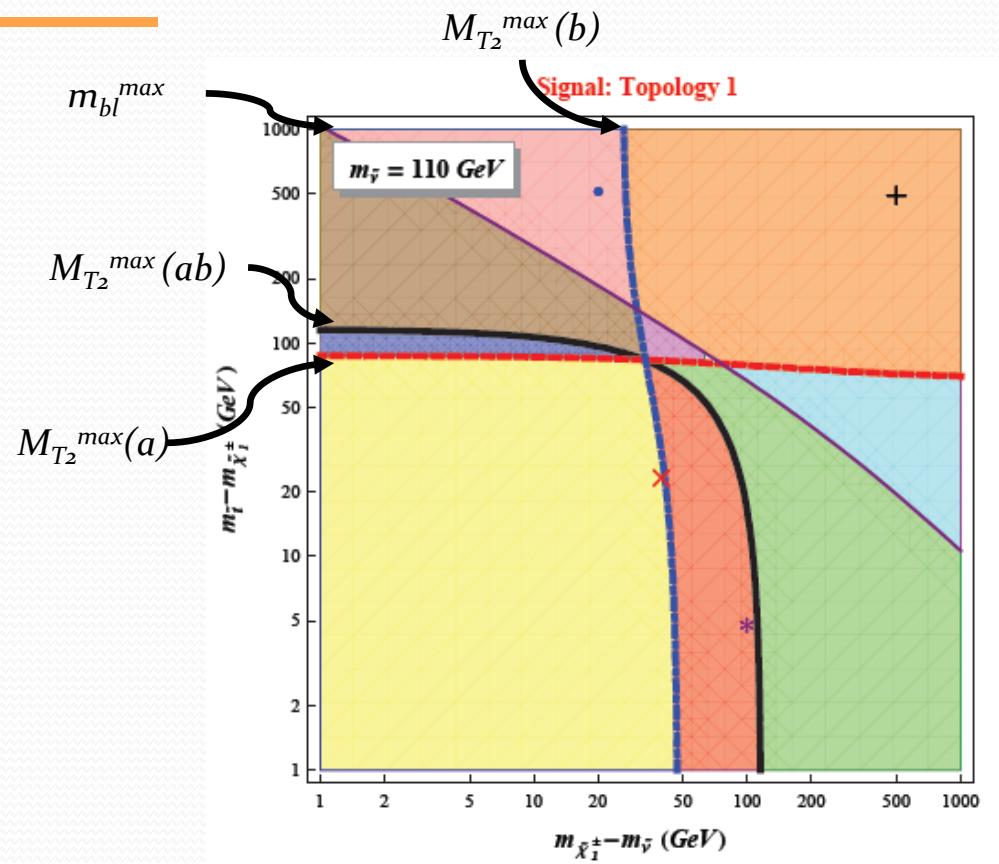


4. New physics search strategies

Case study with Topology 1

- Full signal process





+, •, * : Easy benchmark points

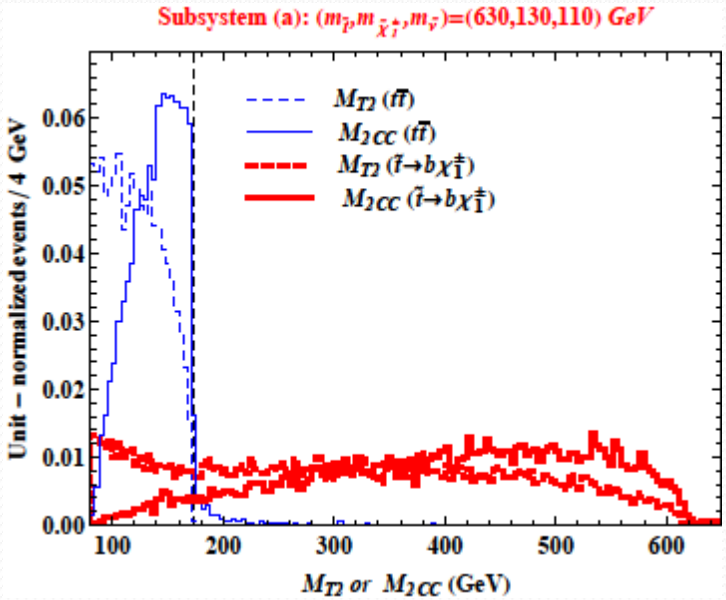
x : unpromising? → discussed later

[W.S.Cho, J.Gainer, DK, K.Matchev, F.Moortgat, L.Pape, M.Park, work in progress]

4. New physics search strategies

Enhanced sensitivity by Property 1

- Enhancing signal strength: remember the moral from Property 1 → more events populated towards the kinematic endpoint as more constraints imposed
- Example mass spectrum: (630, 130, 110) GeV
- Cut-away of background events by M_{2CC} (or M_{2XC}): **saving more signal events**



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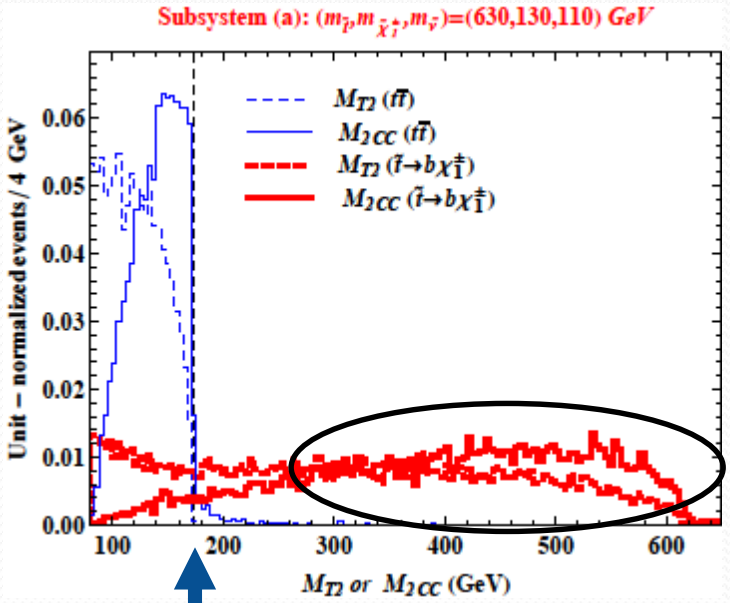

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Enhanced sensitivity by Property 1: Topology 2 only

- The same strategy available
  - ✓ Easy benchmark point with only topology 2 turned on

- Example mass spectrum: (300, 100) GeV
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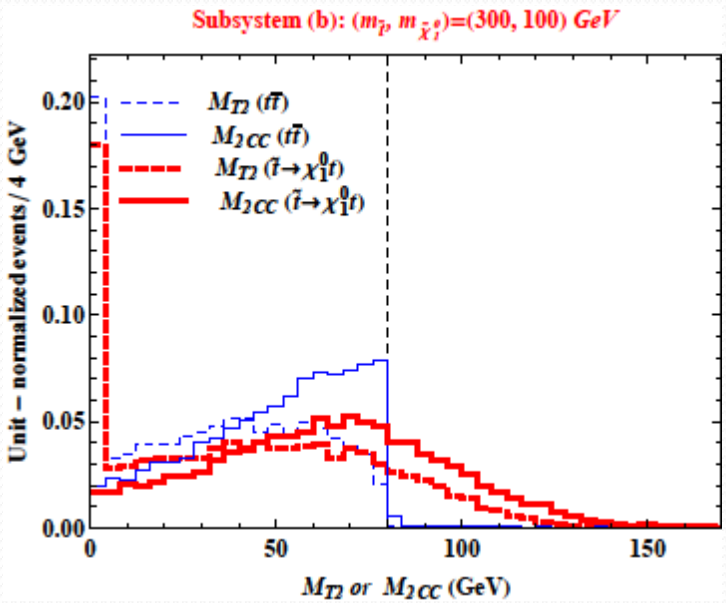
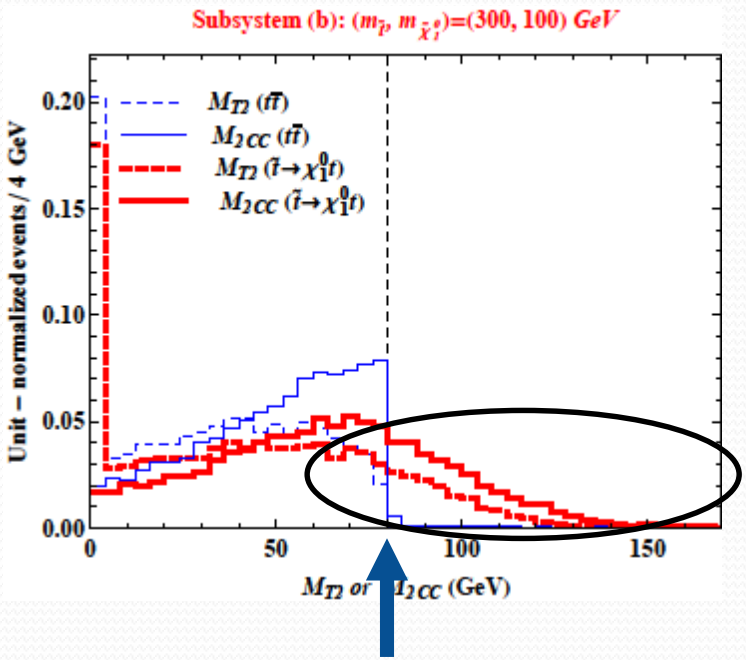


[W.S.Cho, J.Gainer, DK, K.Matchev, F.Moortgat, L.Pape, M.Park, work in progress]

4. New physics search strategies

Enhanced sensitivity by Property 1: Topology 2 only

- The same strategy available
  - ✓ Easy benchmark point with only topology 2 turned on
- Example mass spectrum: (300, 100) GeV
- Cut-away of background events by M_{2CC} (or M_{2XC}): **saving more signal events**



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Unlucky/Challenging case

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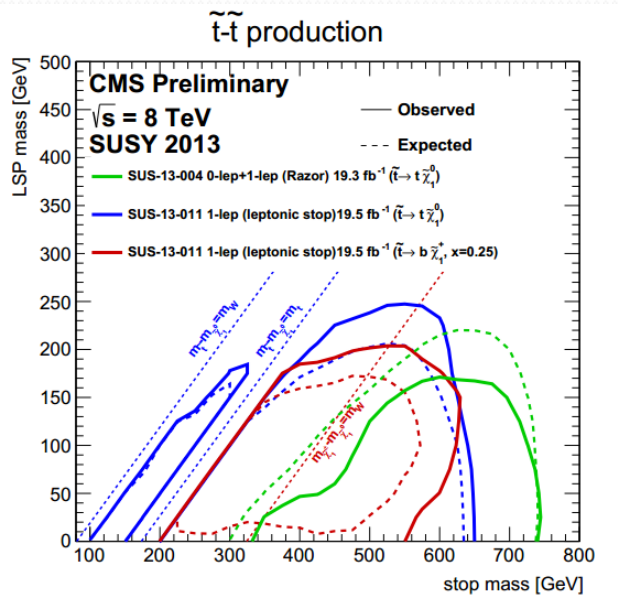

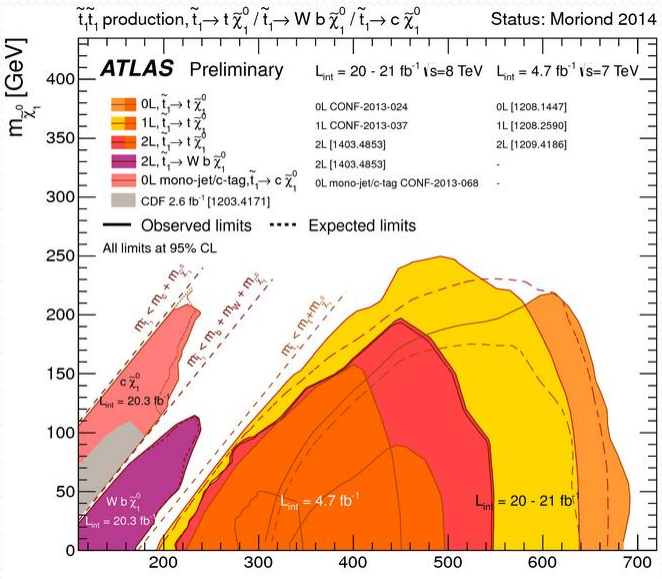

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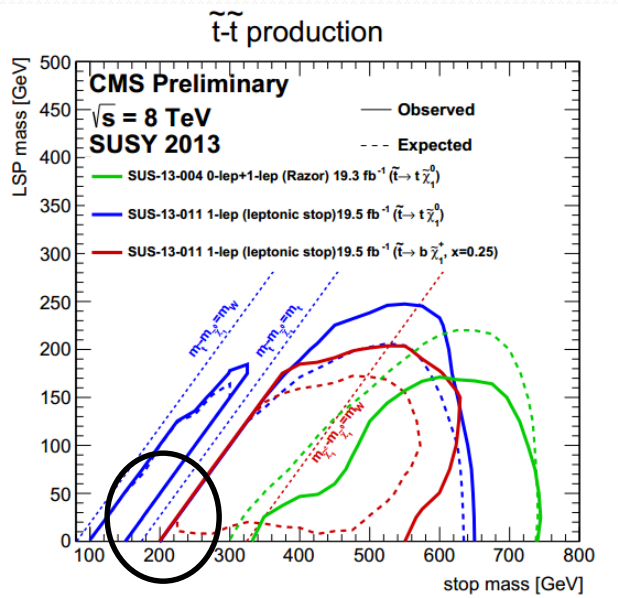
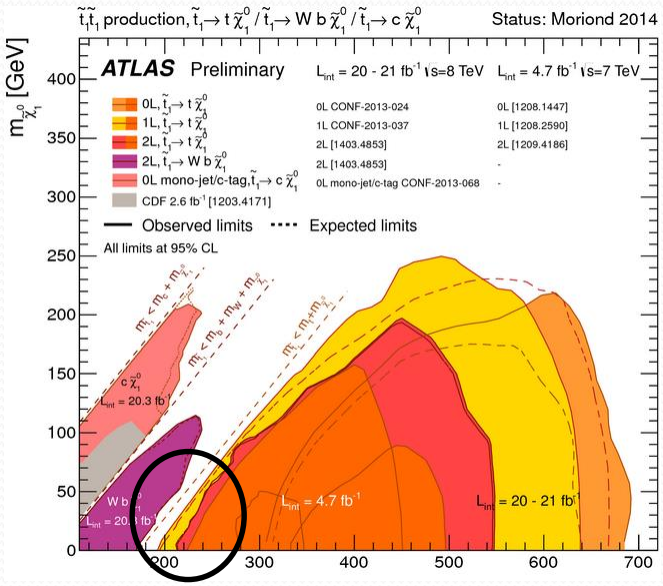


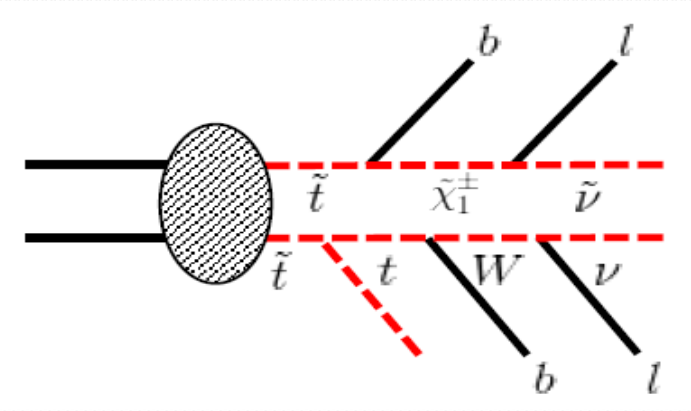


- Similar to ttbar background: hard to probe (with standard tools) !!

4. New physics search strategies

Asymmetric event topology

- Two produced stops going through different decay processes.



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Asymmetric event topology

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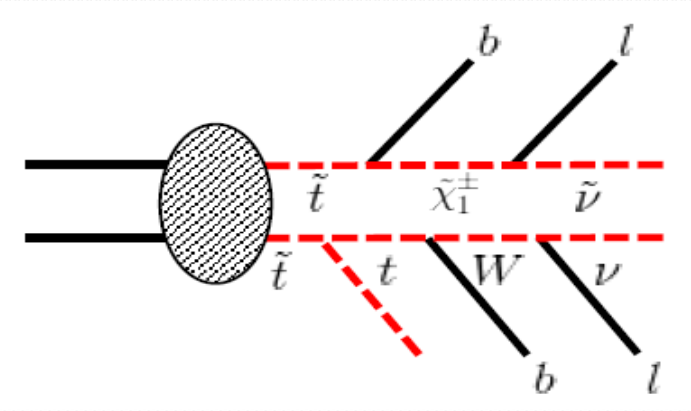
- Main idea [W.S.Cho, J.Gainer, DK, K.Matchev, F.Moortgat, L.Pape, M.Park, to appear soon (2014)]
  - Model assumptions targeted for ttbar decay topology, i.e., symmetric decay process



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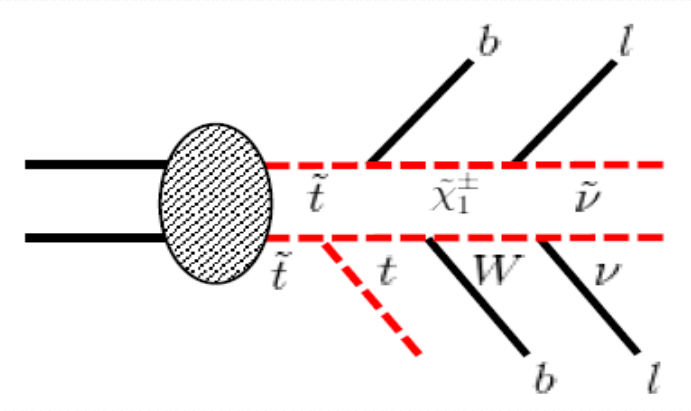

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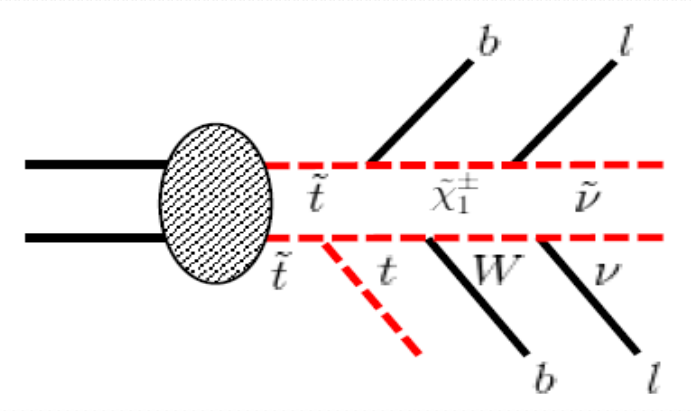
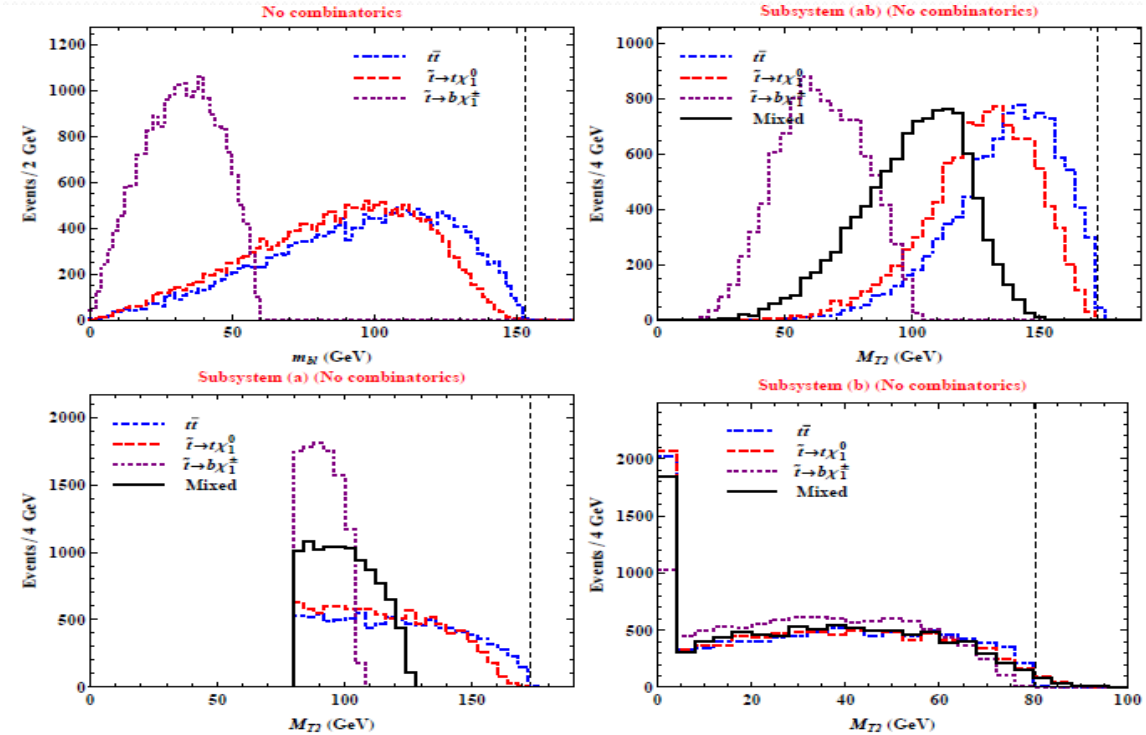
  - Model assumptions targeted for ttbar decay topology, i.e., symmetric decay process
  - Signal process having an asymmetric decay topology, i.e., contradiction to the model assumption
  - Expecting a huge **endpoint violation** due to Property 2



4. New physics search strategies

Standard approach (Preliminary)

- Mass spectrum: 174 GeV – stop, 150 GeV – chargino, 110 GeV – sneutrino, 0 GeV – LSP



[W.S.Cho, J.Gainer, DK, K.Matchev, F.Moortgat, L.Pape, M.Park, work in progress]

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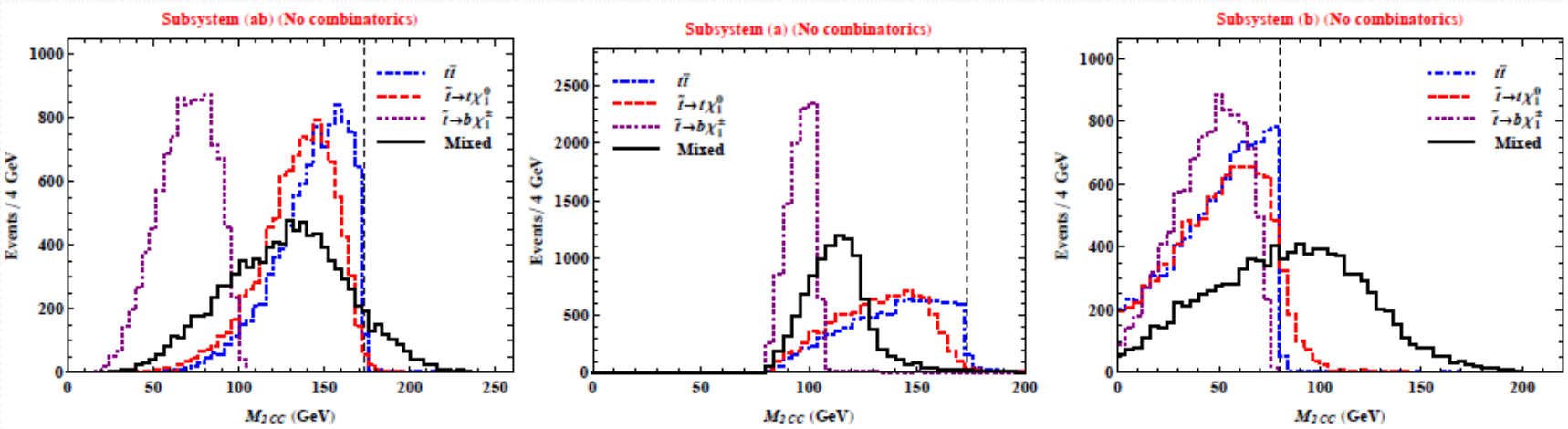
M_{2CC} no combinatorics (Preliminary)

- For mixed event topology, BR assumed 1:1, no combinatorics considered



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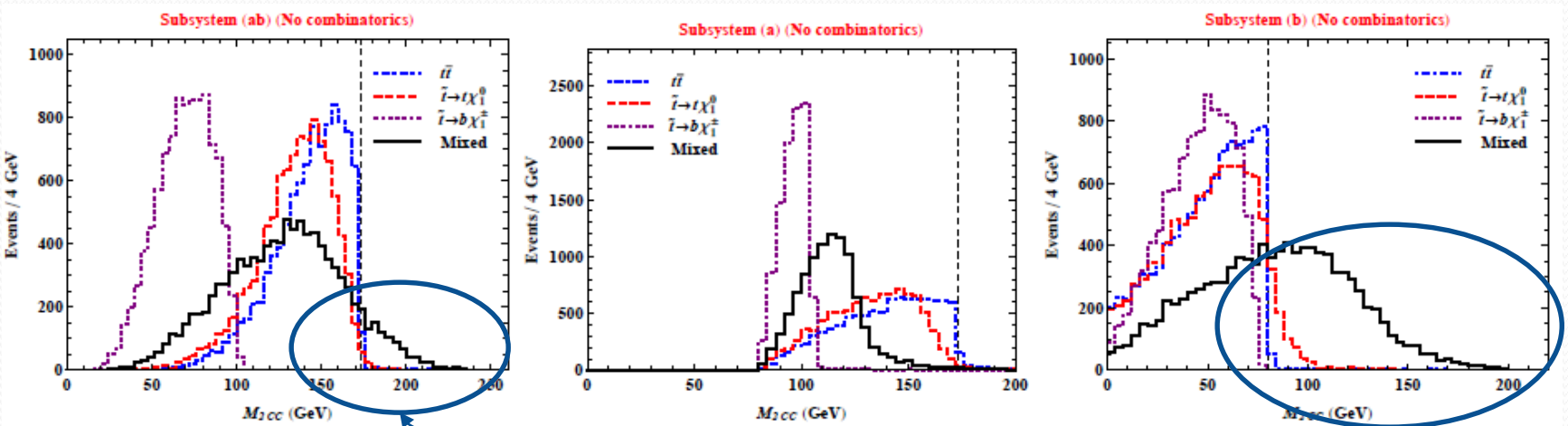

Combination of subsystems (*ab*) and (*b*): ~70% signal events survive!

[W.S.Cho, J.Gainer, DK, K.Matchev, F.Moortgat, L.Pape, M.Park, work in progress]

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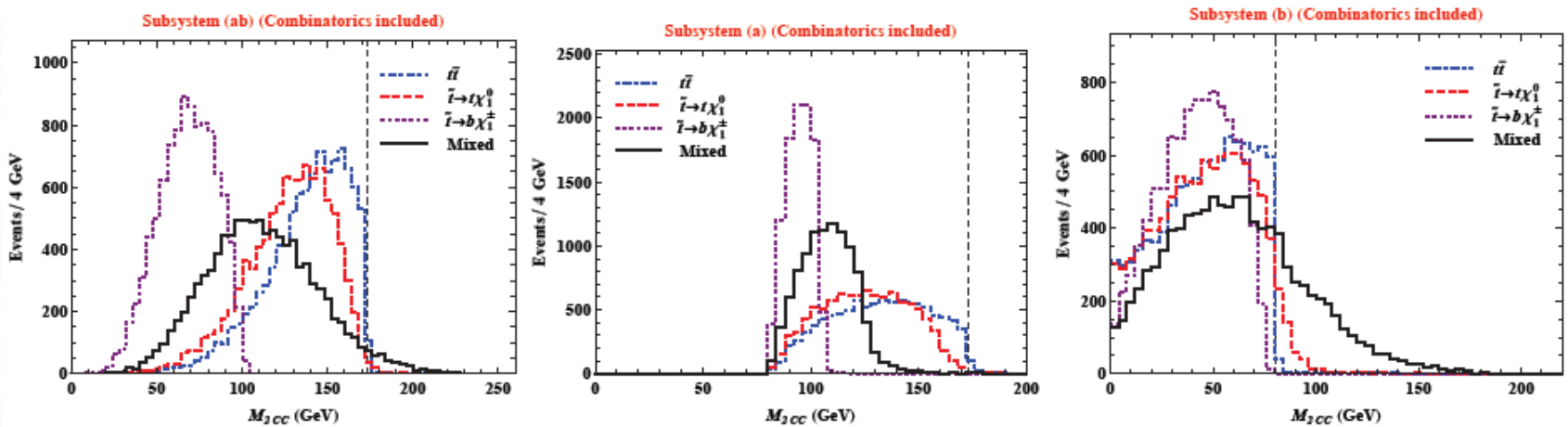

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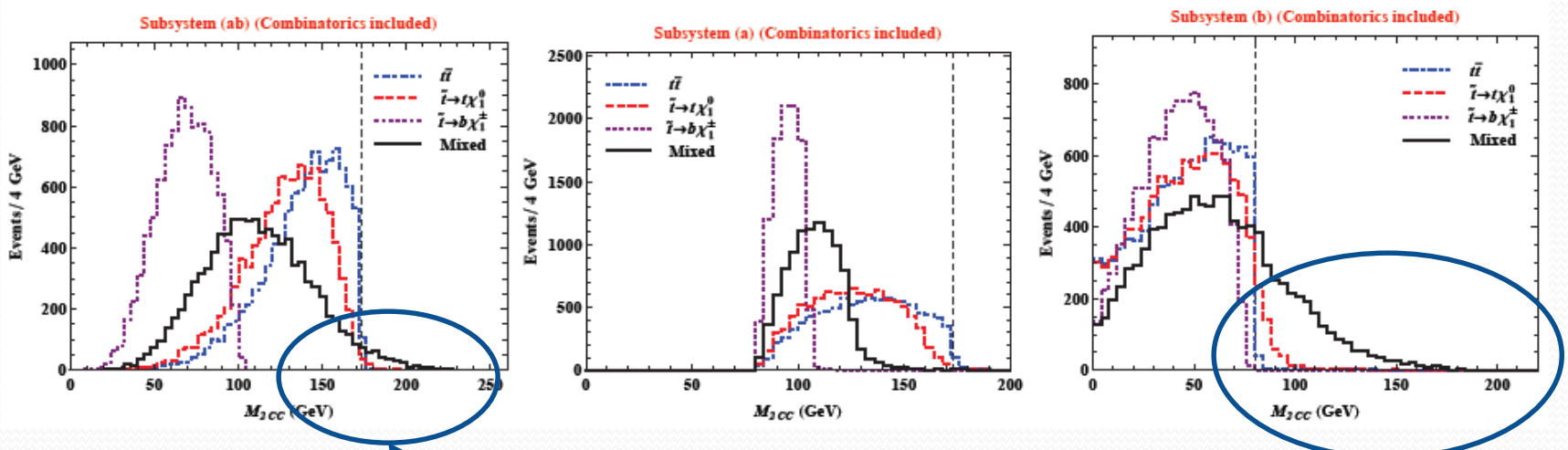


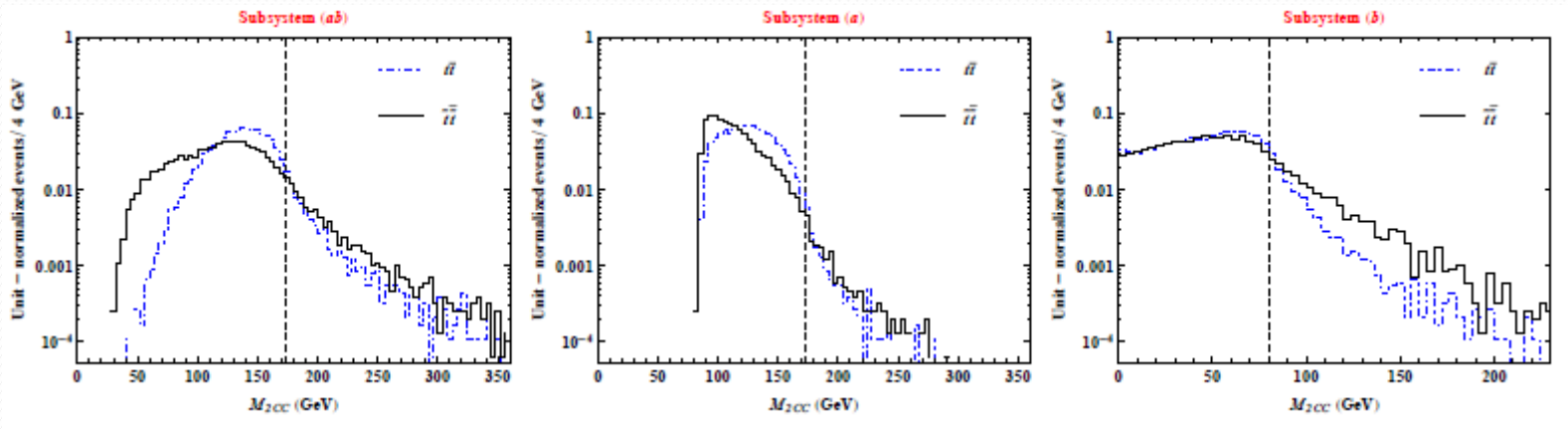
Even with combinatorics included, a large fraction of events survive!

[W.S.Cho, J.Gainer, DK, K.Matchev, F.Moortgat, L.Pape, M.Park, work in progress]

4. New physics search strategies

M_{2CC} detector level (Preliminary)

- Fast simulation with Delphes3
- Realistic (hard) cuts applied to suppress backgrounds other than ttbar [ATLAS-CONF-2013-077]



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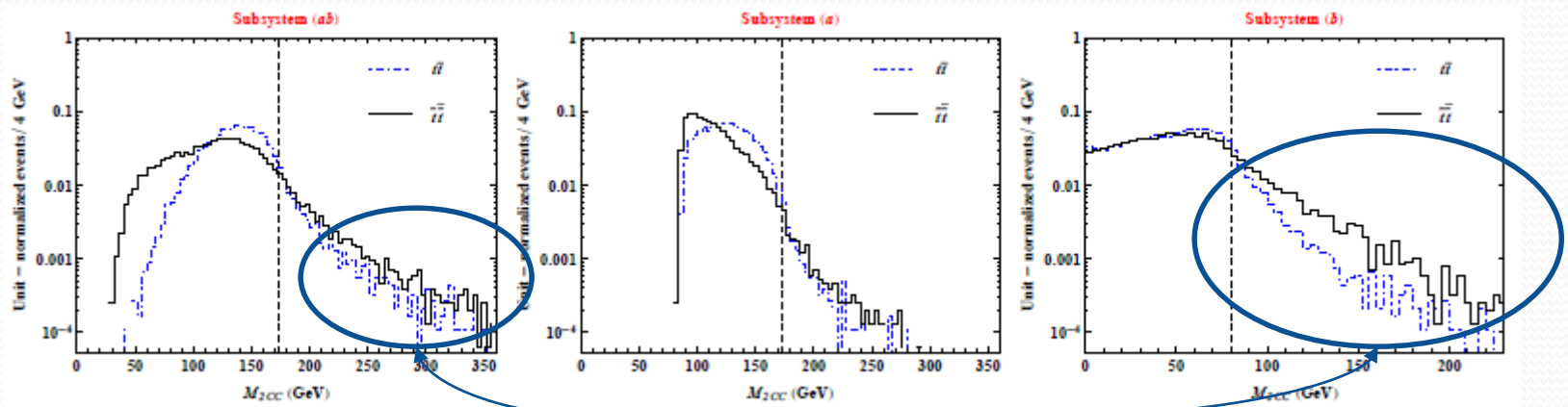


Even at detector level, M_2 variables can be good discriminators!

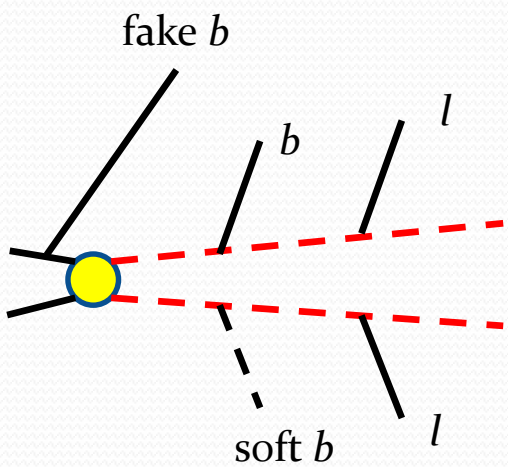
[W.S.Cho, J.Gainer, DK, K.Matchev, F.Moortgat, L.Pape, M.Park, work in progress]

4. New physics search strategies

Why endpoint violation in ttbar?

- Two major causes

  i. 1 regular *b*-tagged jet + 1 soft *b* quark + 1 ISR jet faking another *b*-jet



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Why endpoint violation in ttbar?

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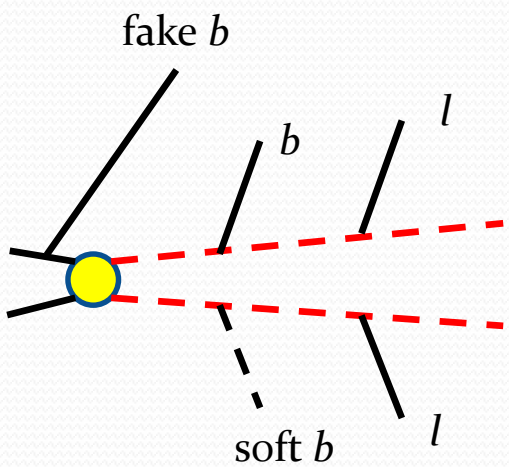
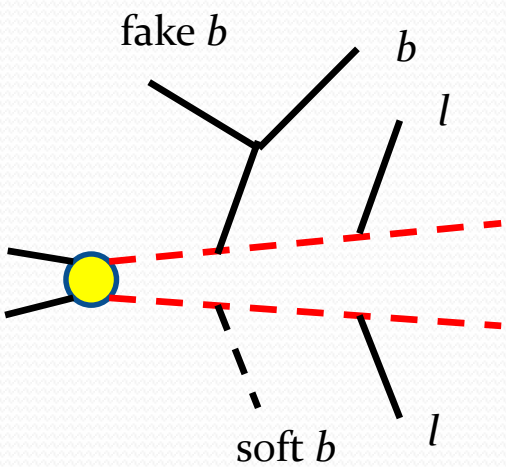
  - i. 1 regular *b*-tagged jet + 1 soft *b* quark + 1 ISR jet faking another *b*-jet
  - ii. 1 soft *b* quark + 1 hard *b* quark split into 1 *b*-tagged jet + 1 FSR jet faking another *b*-jet





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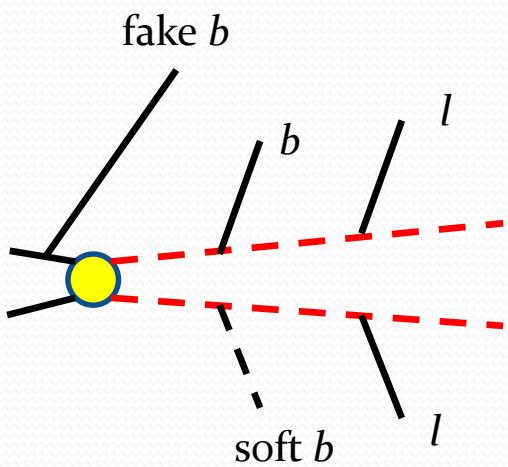
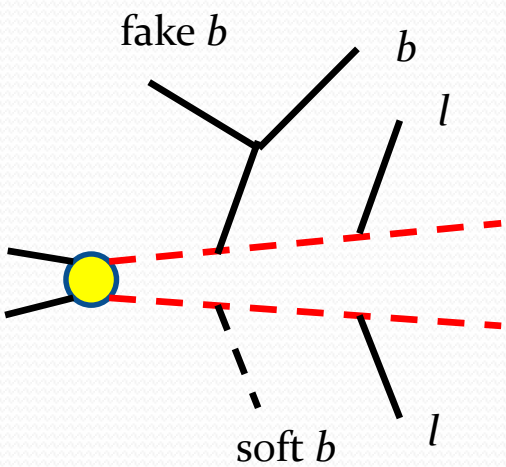




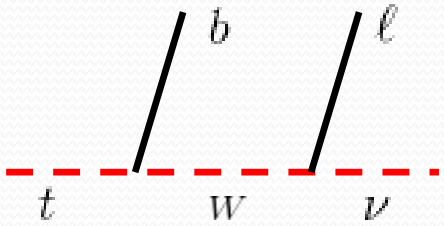
- Better understanding in ISR and FSR enabling better performance of M_2 variables

4. New physics search strategies

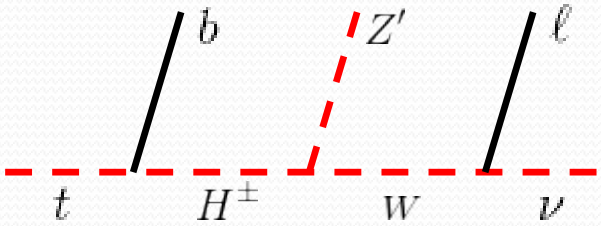
Other possible searches

- Dark Z' search via a rare decay of the top quark [DK, H.S.Lee, and M. Park in progress]
- Mixed event topology between Topology 1 and Topology 3

(a) Topology 1



(b) Topology 3



- Complementary to the study in the context of SUSY search

7. Conclusions

Summary and outlook

- New physics has not discovered yet!
- More signal/background sensitive variables enable us to separate signal and background events more efficiently.
- Recently proposed M_2 variables enable us to probe challenging regions where new physics would be hidden.
- Stop search was discussed as a concrete example.
- More interesting results/physics with M_2 variables will come up. Stay tuned!

Thank you!