Resolving combinatorial ambiguity in missing energy events

Dipsikha Debnath
University of Florida

Work with Doojin Kim, Jeong Han Kim, K. C. Kong, K. Matchev

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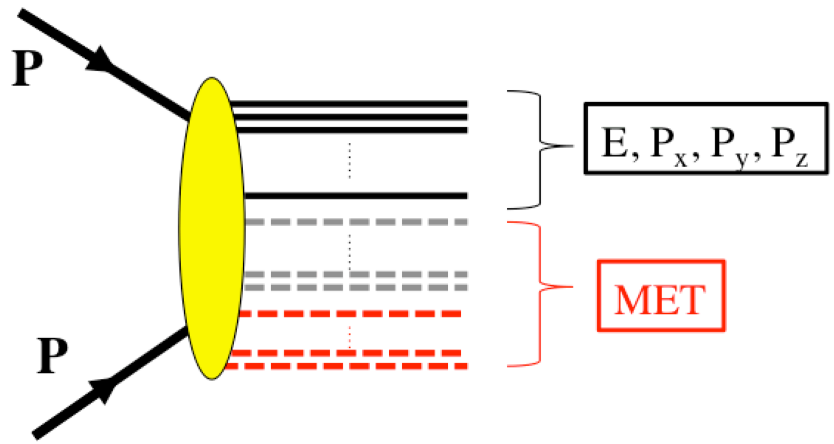
Missing Energy events at the LHC

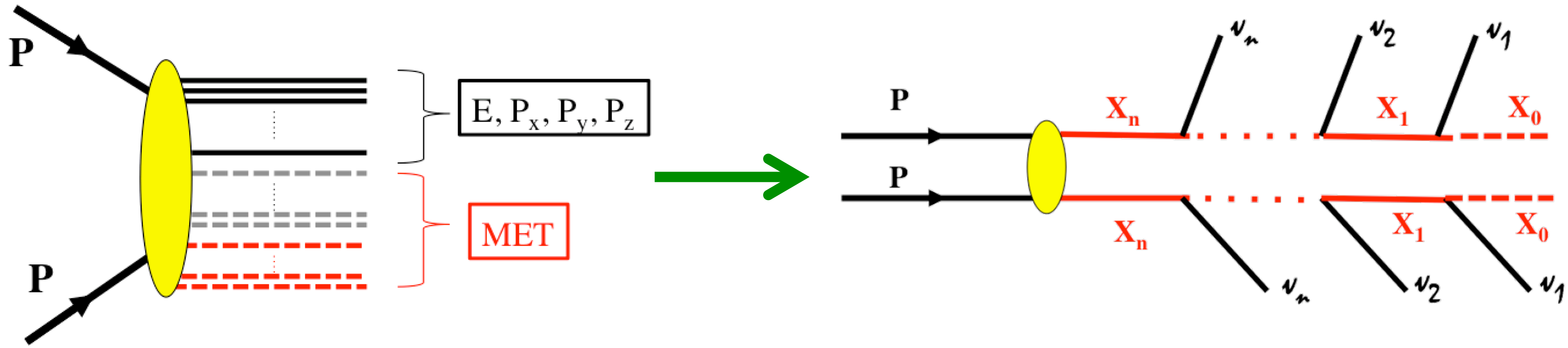
- Events with MET are exciting – offer possibility of a Dark Matter discovery



- MET ($\vec{\not{P}}_T$) events are challenging to interpret and analyze.
  - Incomplete kinematic information (only $\vec{\not{P}}_T$ is measured)
  - Detector resolution, mismeasurement of visible particles' momenta affects $\vec{\not{P}}_T$ measurement
  - Unknown nature of invisible particles (neutrinos or new particles)

What to do with the unknown missing momenta?

Guess the missing momenta



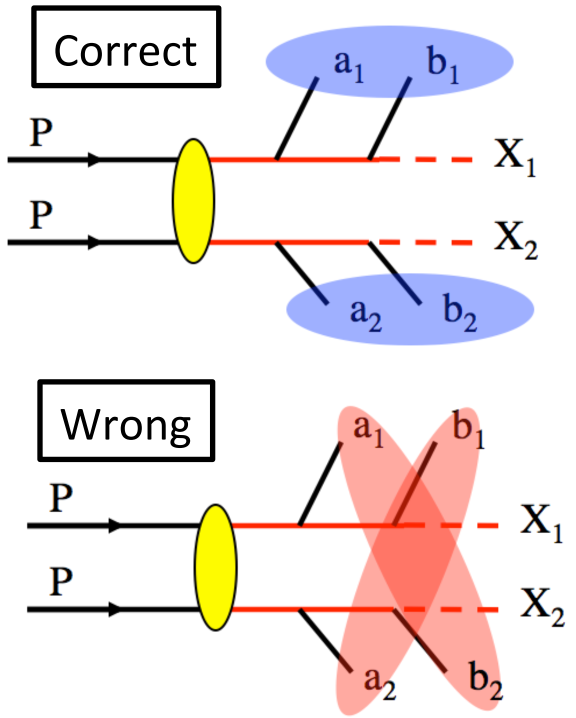
- Hypothesize a certain event topology and obtain the invisible momenta by optimizing a suitable kinematic function.
  - M_{T2}-Assisted On-Shell (MAOS) method determines $\mathbf{p_T}$ and $\mathbf{p_z}$.

    [Cho, Choi, Kim, Park [2008]]

  - M_{2CC} method determines $\mathbf{p_T}$ and $\mathbf{p_z}$ simultaneously.

    [Cho, Gainer, Kim, Matchev, Moortgat, Pape, Park [2014]]

Combinatorial ambiguity

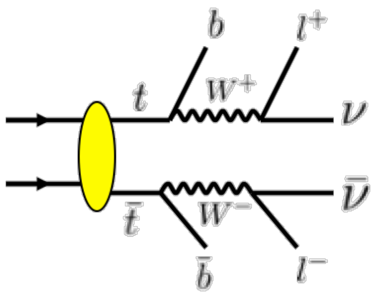


- Combinatorial problem: how to associate final state particles in a given event topology
- The ambiguity issue is severe in MET events as the invariant mass resonance method does not apply.
- Missing particles' momenta are wrongly determined.
- Too complicated if decay chains are longer.

- Why should we care to solve combinatorial issue?

  -Measurement of particle properties such as mass, spin, coupling etc.
  -Finding correct combination in new physics search could improve signal sensitivity

Kinematics of ttbar dilepton event

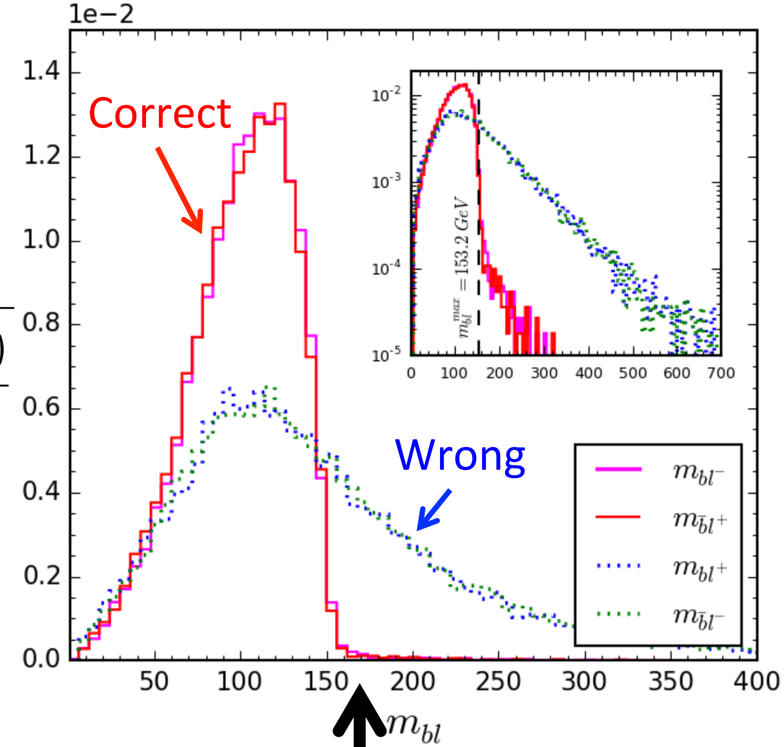


Invariant mass of b quark and lepton system : $\mathbf{m_{bl}}$

- m_{bl} distribution for correct partition is bounded by the endpoint m_{bl}^{max}

$$max\{m_{bl^+}, m_{\bar{b}l^-}\} \leq m_{bl}^{max}$$

$$= \sqrt{\frac{\left(m_{top}^2 - m_W^2\right)\left(m_W^2 - m_\nu^2\right)}{m_W^2}}$$

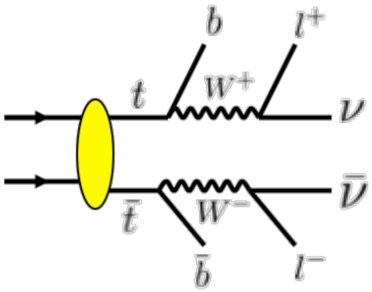


- The wrong partition often violates the endpoint, and it is unbounded

- We can use end-point violations as criterion for distinguishing the correct and wrong partitions.

m_{bl}^{max}

Kinematics of ttbar dilepton event



Mass constraining variable: M_{2CC}

- Scanning of the four momentum of neutrinos with constraints

$$M_{2CC}(m_\nu^{test}) \equiv \min_{\vec{p}_\nu, \vec{p}_{\bar{\nu}}} \left[max\{M_t(\vec{p}_\nu, m_\nu^{test}), M_{\bar{t}}(\vec{p}_{\bar{\nu}}, m_\nu^{test})\}\right]$$

reconstructed parent mass

MET: $\vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T} = \vec{\not{P}}_T$

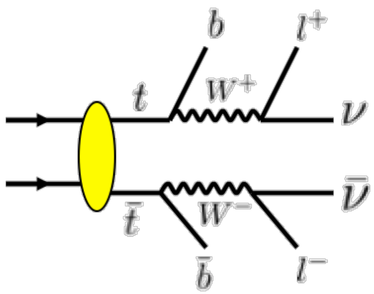
Constraints:
$$M_{W^+} = M_{W^-}$$
$$M_t = M_{\bar{t}}$$

1401.1449, Cho, Gainer, Kim, Matchev, Moortgat, Pape, Park (2014)

- M_{2CC} provides an ansatz for the four-momentum of missing particles including longitudinal components using the constraints.

Kinematics of ttbar dilepton event

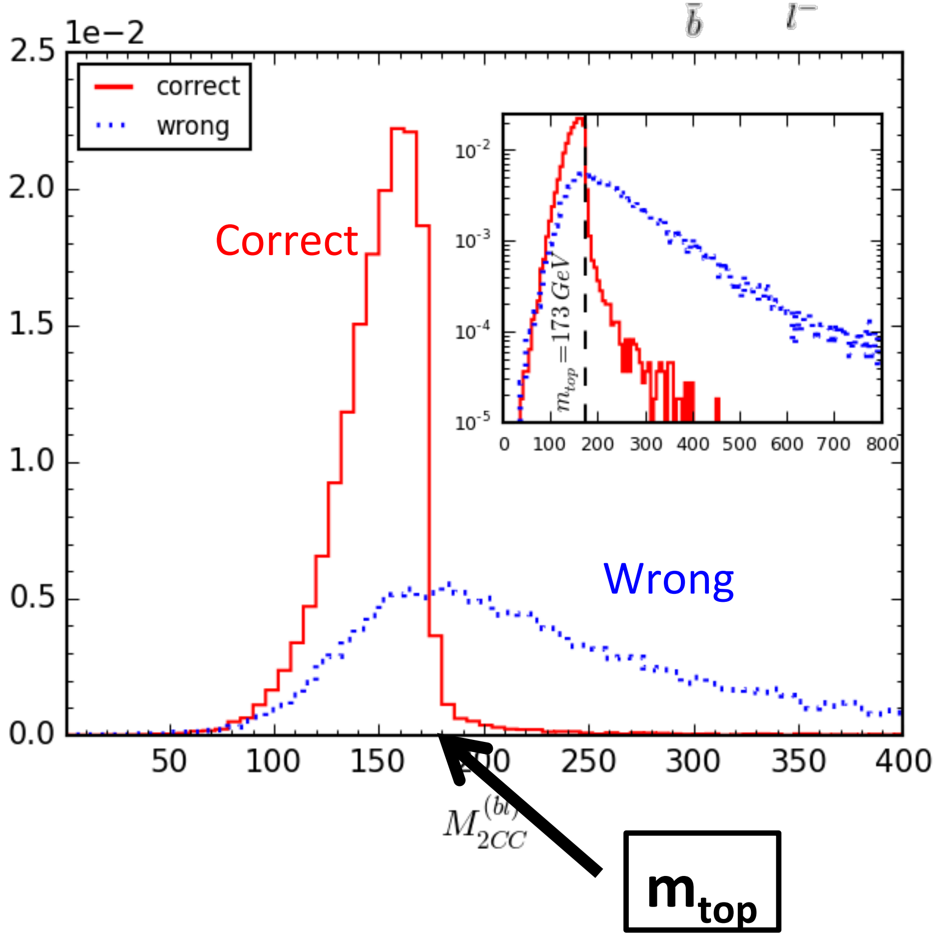
Mass constraining variable: M_{2CC}



- For the correct partition M_{2CC} is bounded by the endpoint; the top mass

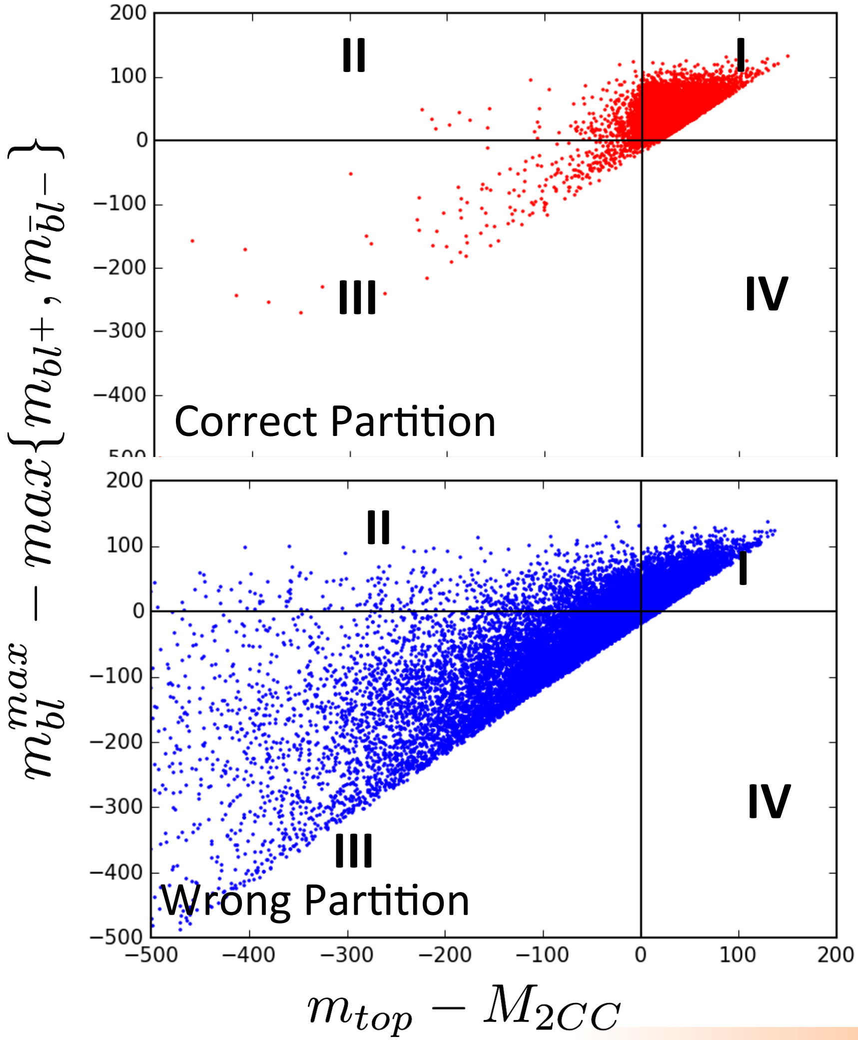
- M_{2CC} for wrong partition is unbounded.

- Same as m_{bl}; we can use end-point violations as criterion for distinguishing the correct and wrong partitions.



M_{bl} - M_{2CC} combination

- Partitions which fail to satisfy the endpoints are wrong partitions.



Quadrant counts based on $M_{2CC}^{(b\ell)}$ and $m_{b\ell}$

Quadrant for P_C	Quadrant for P_W I	II	III	IV
I	4494	2317	10222	217
II	168	178	480	5
III	37	26	251	1
IV	17	3	38	2

Total events 18456

Green: Correctly resolved

Red: Wrongly resolved

White: Unresolved

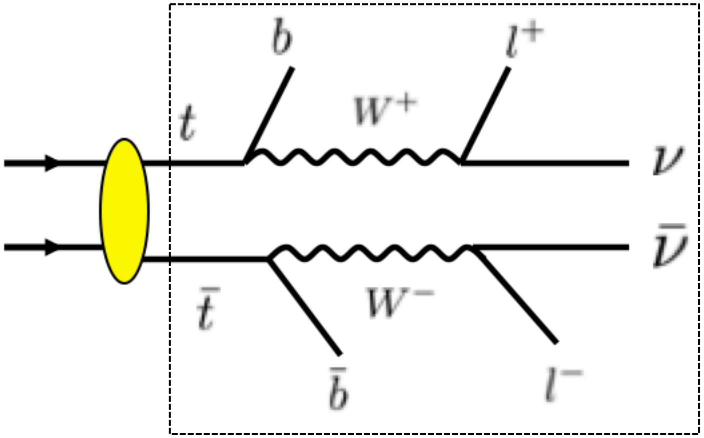
With this method the efficiency of tagging correct partitions is 85 %

[Debnath, Han, Kim, Kong, Matchev (2017)]


We could use subsystem M_2 variables
Is 85 % good enough?

The subsystem variables

Subsystem (bl):



$$M_{2CW}^{(bl)}(m_\nu^{test}) \equiv \min_{\vec{p}_\nu,\vec{p}_{\bar{\nu}}} \left[max\{M_t(\vec{p}_\nu, m_\nu^{test}), M_{\bar{t}}(\vec{p}_{\bar{\nu}}, m_\nu^{test})\}\right]$$

$$\vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T} = \vec{\not{P}}_T$$

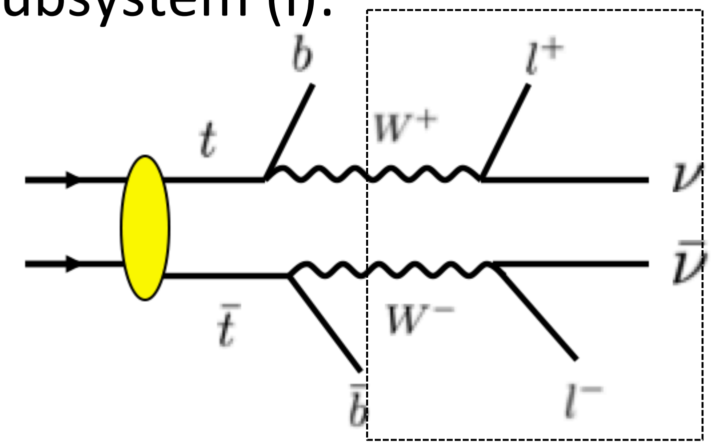
$$M_t = M_{\bar{t}}$$

$$\boxed{M_{W+}^2 = M_{W-}^2 = (81.4GeV)^2}$$

Extra constraint

Endpoint of M_{2CW} : m_{top}

Subsystem (l):



$$M_{2Ct}^{(l)}(m_\nu^{test}) \equiv \min_{\vec{p}_\nu,\vec{p}_{\bar{\nu}}} \left[max\{M_{W^+}(\vec{p}_\nu, m_\nu^{test}), M_{W^-}(\vec{p}_{\bar{\nu}}, m_\nu^{test})\}\right]$$

$$\vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T} = \vec{\not{P}}_T$$

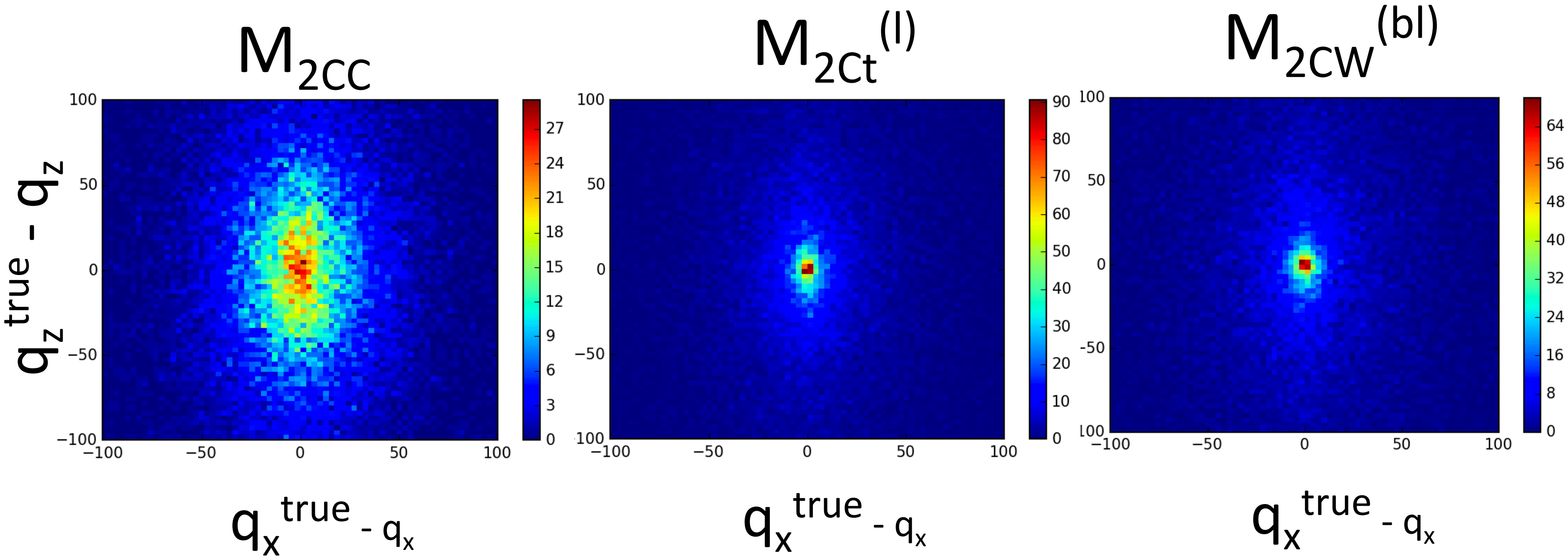
$$\boxed{M_t^2 = M_{\bar{t}}^2 = (173GeV)^2}$$

Extra constraint

$$M_{W^+} = M_{W^-}$$

Endpoint of M_{2Ct} : m_W

Improvement over M_{2CC}

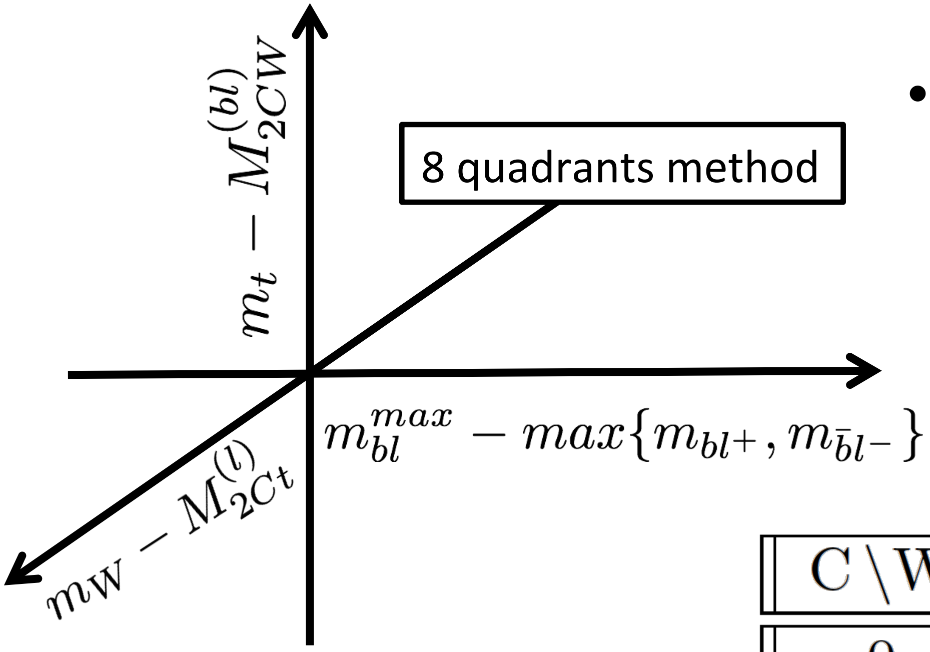


Both transverse and longitudinal components of invisible particle momenta are determined more accurately with M_{2Ct} and M_{2CW} than M_{2CC}.

Additional mass information definitely helps

M_{bl}, M_{2Ct}, M_{2CW} combined method

- Replace M_{2CC} by M_{2Ct} and M_{2CW}. Distributions for the correct partition are bounded by the endpoints



- We declare partition with fewer endpoint violations as correct partition.

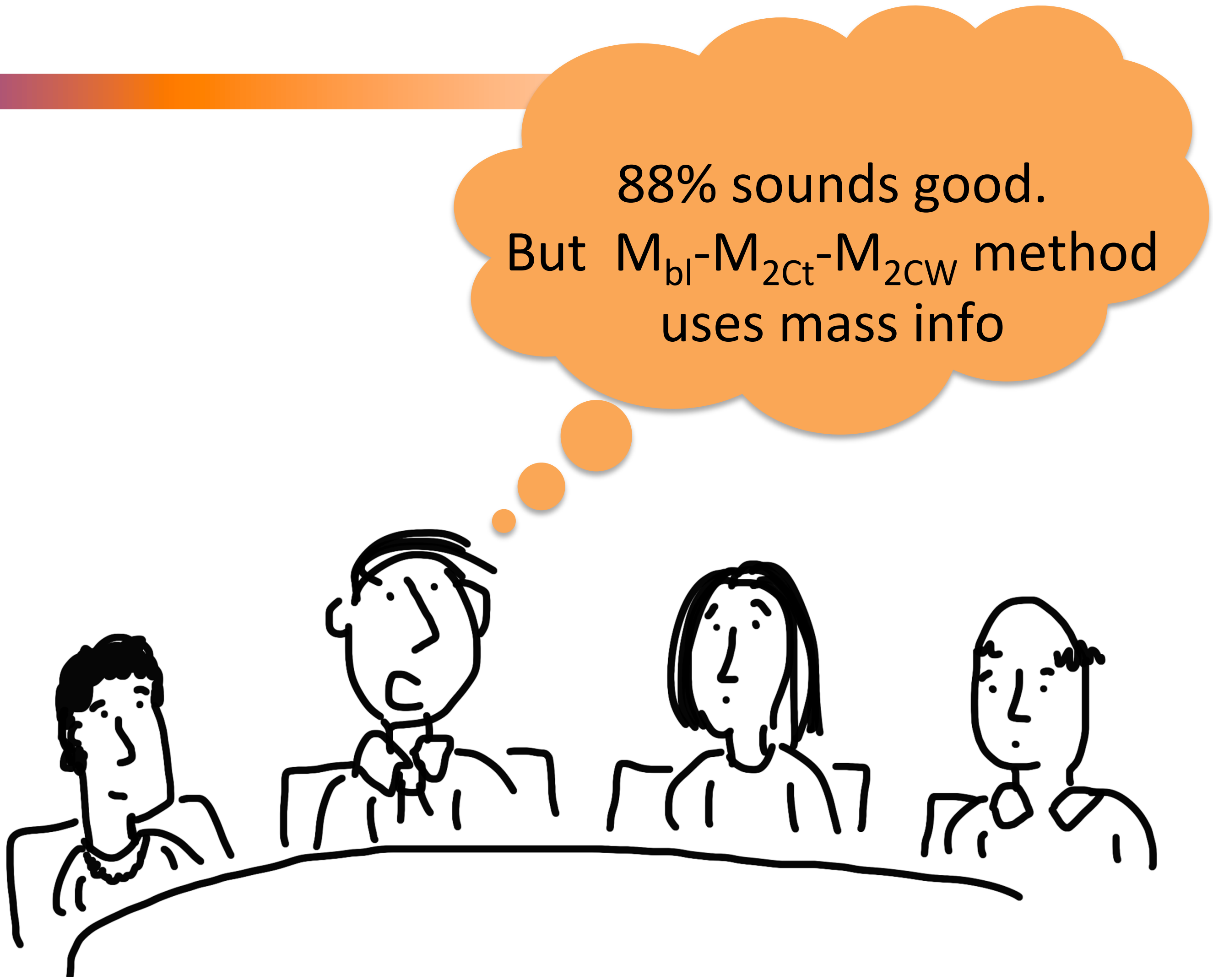
Green: Correctly resolved
Red: Wrongly resolved
White: Unresolved

Efficiency of tagging correct partition = 88%

Count based on endpoint violations

C \ W	0	1	2	3
0	2,277	887	2,663	8,425
1	260	152	357	1,376
2	191	95	508	949
3	21	8	35	252

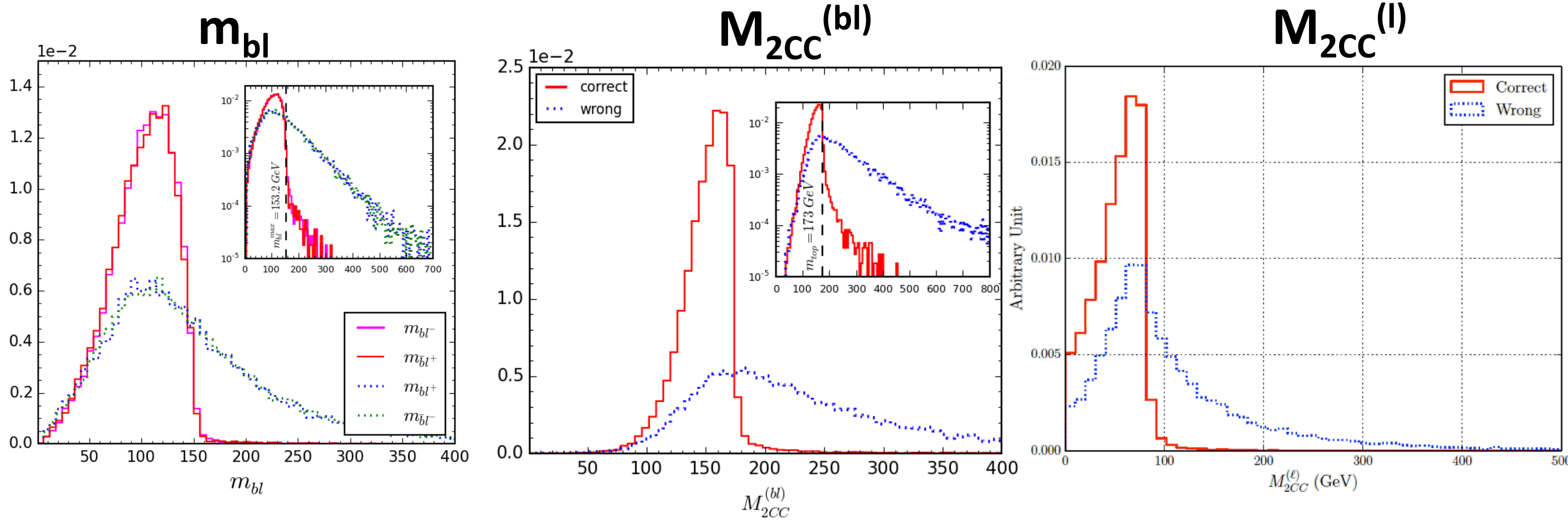
N_{total} = 18456



How to generalize the method in BSM scenarios?

No mass, no endpoint information

- Distributions for wrong partitions are broader compared to correct partitions.



Red: Correct, Blue: Wrong

- We consider this behavior as a criteria to discriminate between correct and wrong partitions.

No mass, no endpoint information

- We use three variables m_{bl}, M_{2CC}, $M_{2CC}^{(l)}$. These variables do not require mass information of parent particles.

$$T_1 = max\{m_{bl^+}, m_{\bar{b}l^-}\}, T_5 = M_{2CC}^{(bl)}, T_6 = M_{2CC}^{(l)}$$

$$\Delta T = T(wrong) - T(correct)$$

No mass constraint is used

- ΔT is expected to be positive (+) for correctly resolved events.

Event counts based on combined ΔT method

$(\text{sign}(\Delta T_1(P_W, P_C)), \text{sign}(\Delta T_5(P_W, P_C)), \text{sign}(\Delta T_6(P_W, P_C)))$							
$(+++)$	$(++-)$	$(+-+)$	$(-++)$	$(+--)$	$(-+-)$	$(--+)$	$(---)$
12,301	2,376	175	856	318	147	1,017	1,266

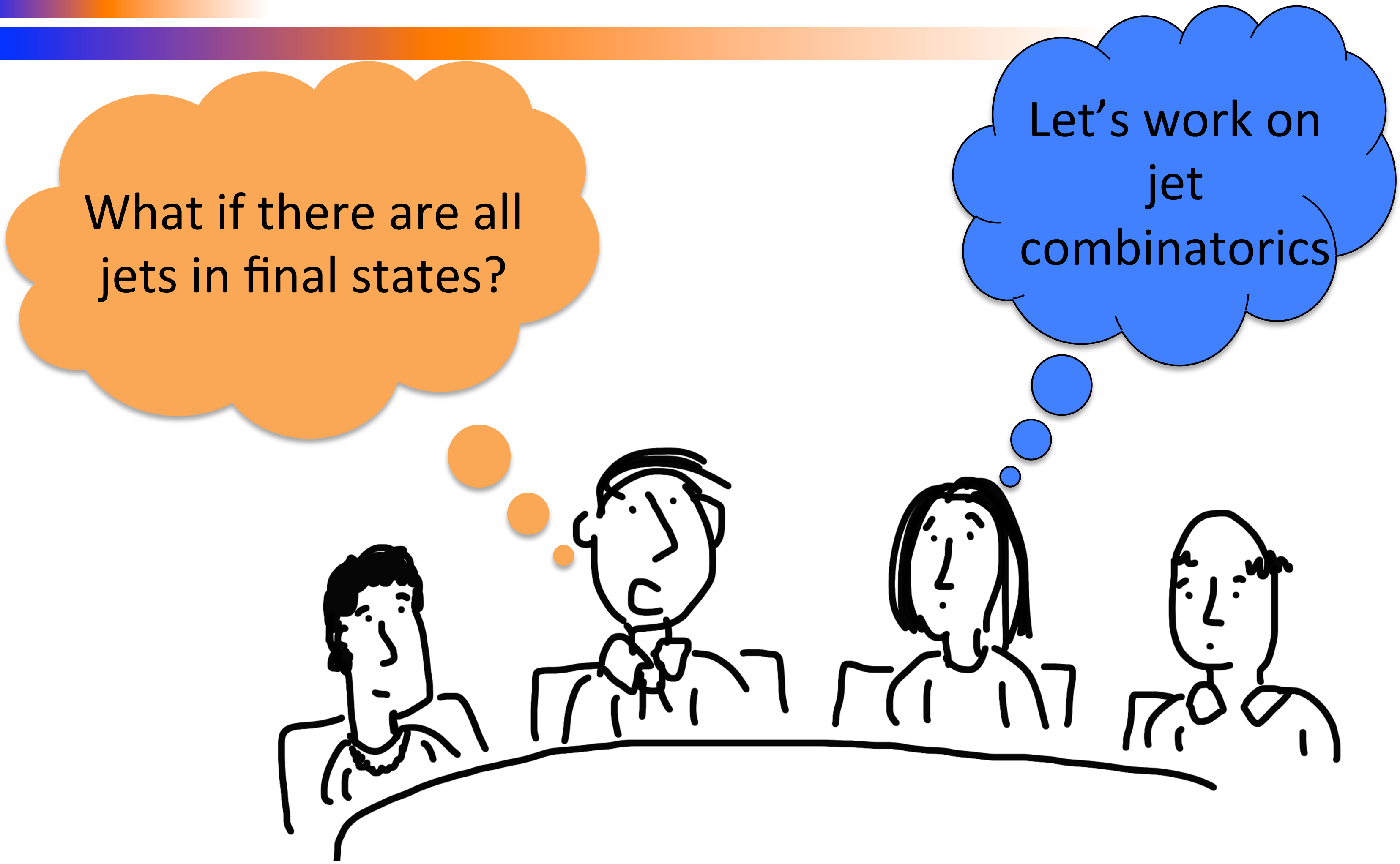
Green: Correctly resolved, Red: Wrongly resolved

N_{total} = 18456

Efficiency of tagging correct partition = 85 %

Summary

- Constrained M_2 variables provide unique momenta of invisible particles.
- When combined with mass information (like top or W mass in dilepton ttbar topology), precision on momentum reconstruction improves significantly.
- Two fold ambiguity can be resolved with a high efficiency with constrained M_2 .
- Full momentum reconstruction of dilepton ttbar topology is possible at high precision, without using matrix element.
- Application in any two step two body decay is possible.

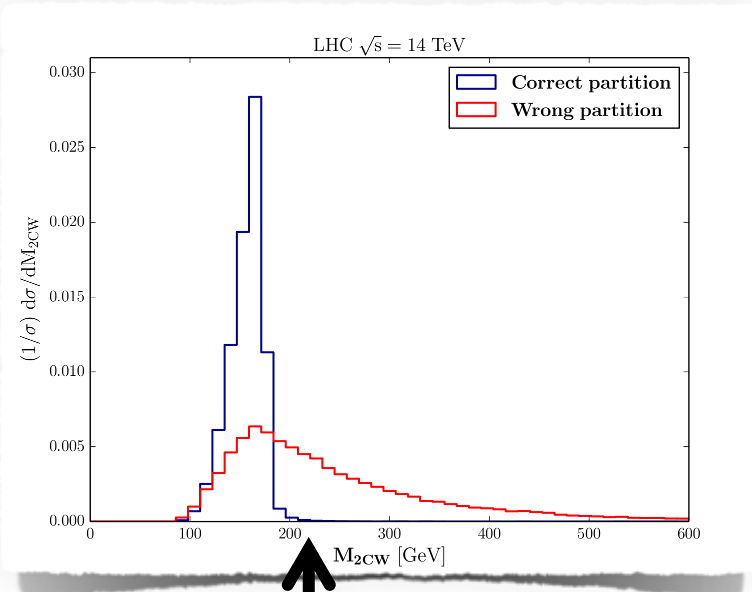

What if there are all jets in final states?
Let's work on jet combinatorics

Stay Tuned!

Back Up Slides

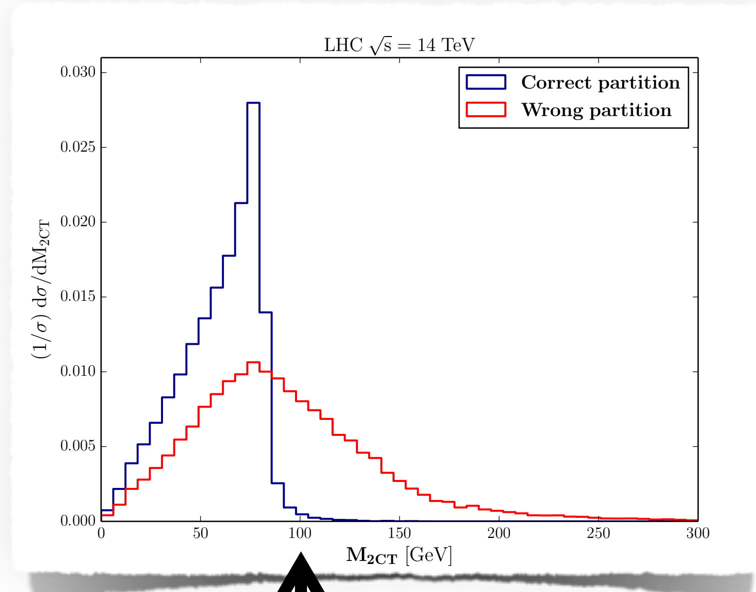
The subsystem variables

M_{2CW}



m_{top}

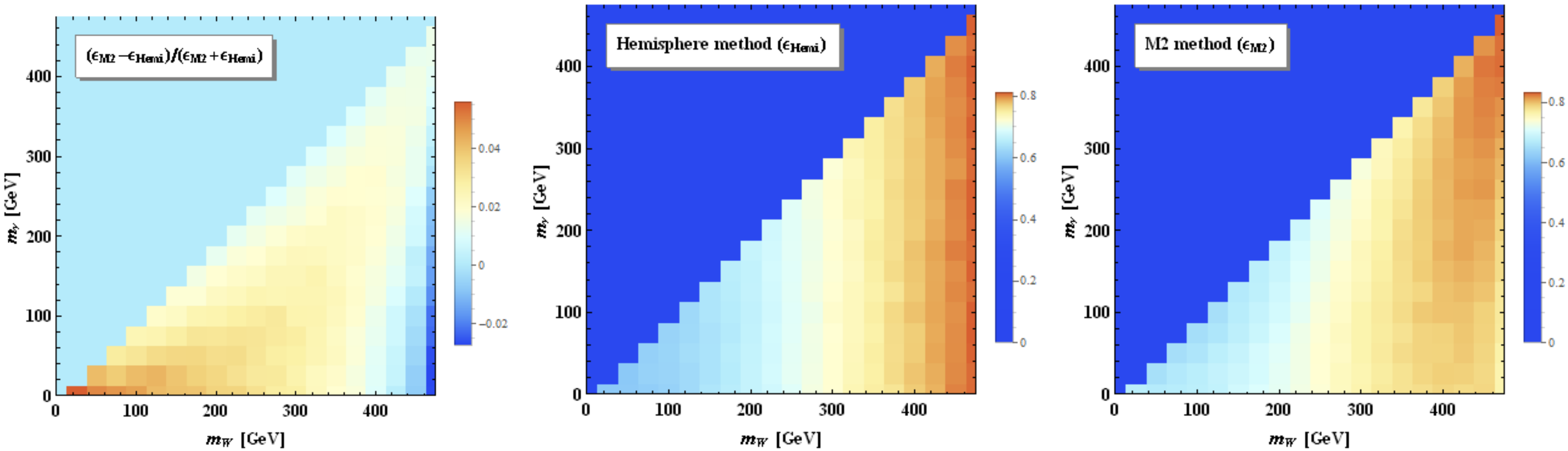
M_{2Ct}



m_W

Comparison with hemisphere method

Hemisphere method: Clusters the visible particles into two groups trying to keep the invariant mass of each cluster to a minimum.



- Both methods seem to work well.
- ΔT's method works better when MW is small.
- The hemisphere method performs better when MW is large.