# Recursive Jigsaw Reconstruction

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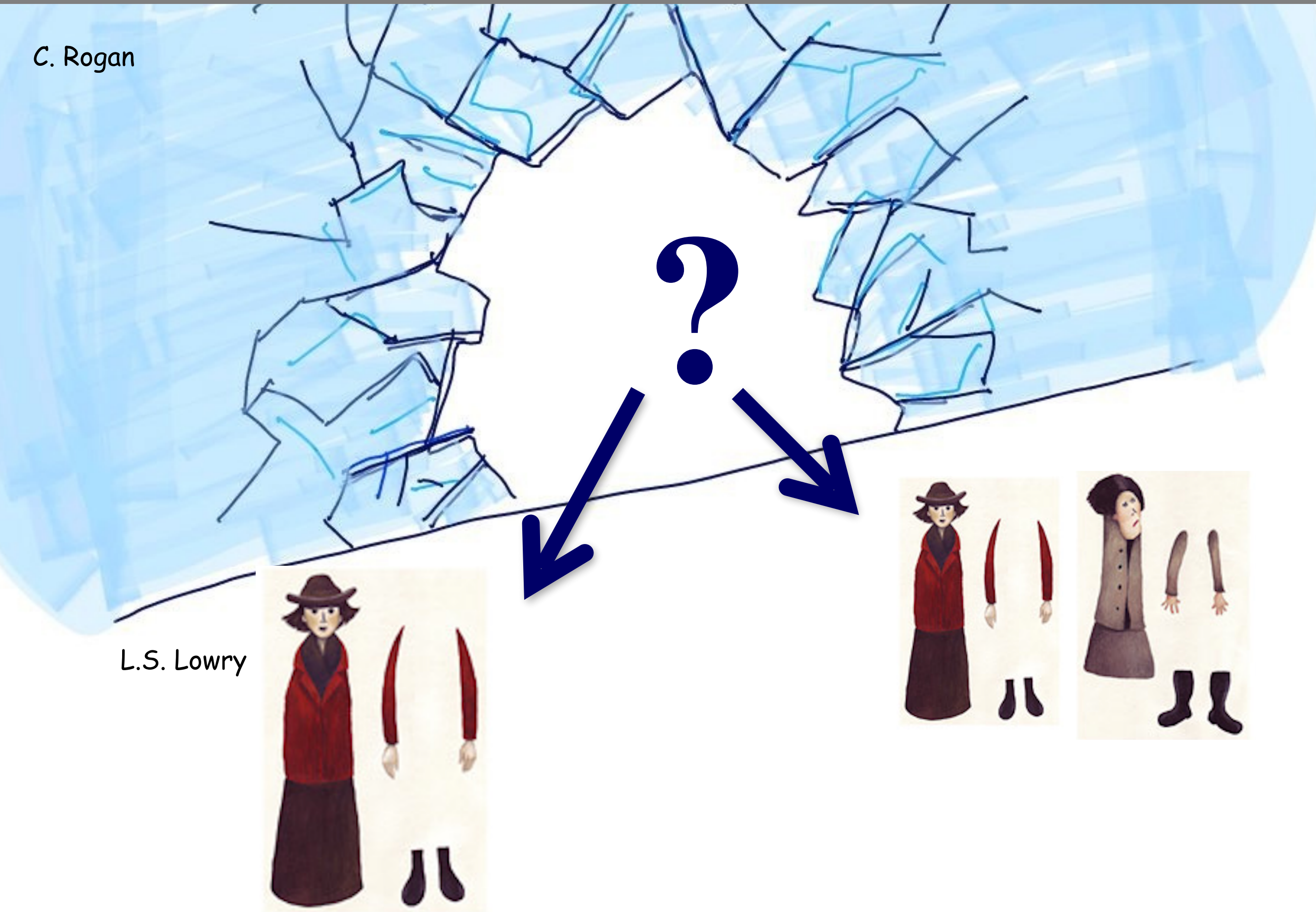
CoEPP
ARC Centre of Excellence for
Particle Physics at the Terascale

- Weakly interacting particles and open final states – what and why?
- Recursive Jigsaw reconstruction: towards a kinematic basis for open final states
- Examples:
  - ttbar from resonance production
  - top/stop pair production
- Outlook

# Missing Transverse Momentum



C. Rogan

L.S. Lowry

$$\vec{E}_T^{miss} \equiv -\sum_i^{\text{calo}} \vec{E}_T^{\,i}$$

Infer presence of weakly interacting particles in LHC events by looking for missing transverse energy…..may be composed of one or more objects, which may differ

L.S. Lowry

We can learn more by using other information in an event to contextualize the missing transverse momentum ⇒ multiple weakly interacting particles?

# New approach to reconstructing open final states:

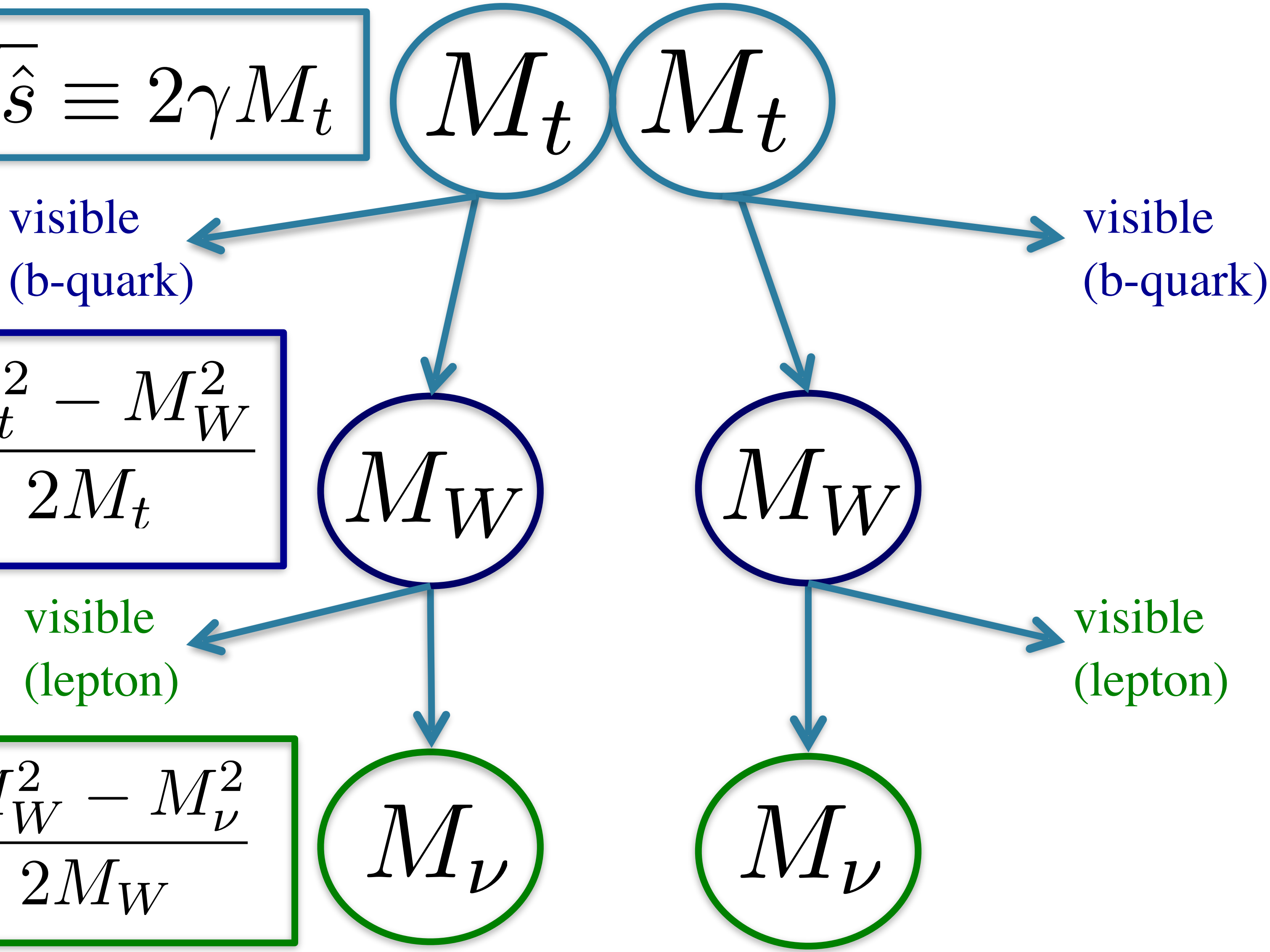
- The strategy is to transform observable momenta iteratively ***reference-frame to reference-frame***, traveling through each of the reference frames relevant to the topology
- At each step, ***extremize only the relevant d.o.f. related to that transformation***
- Repeat procedure recursively according to particular rules defined for each topology (the topology relevant to each reference frame)

See talk by Chris Rogan on Tuesday for applications to one-step decays and more details on the approach

$$\sqrt{\hat{s}} \equiv 2\gamma M_t$$

$$E_b \equiv \frac{M_t^2 - M_W^2}{2M_t}$$

$$E_{\text{lep}} \equiv \frac{M_W^2 - M_\nu^2}{2M_W}$$

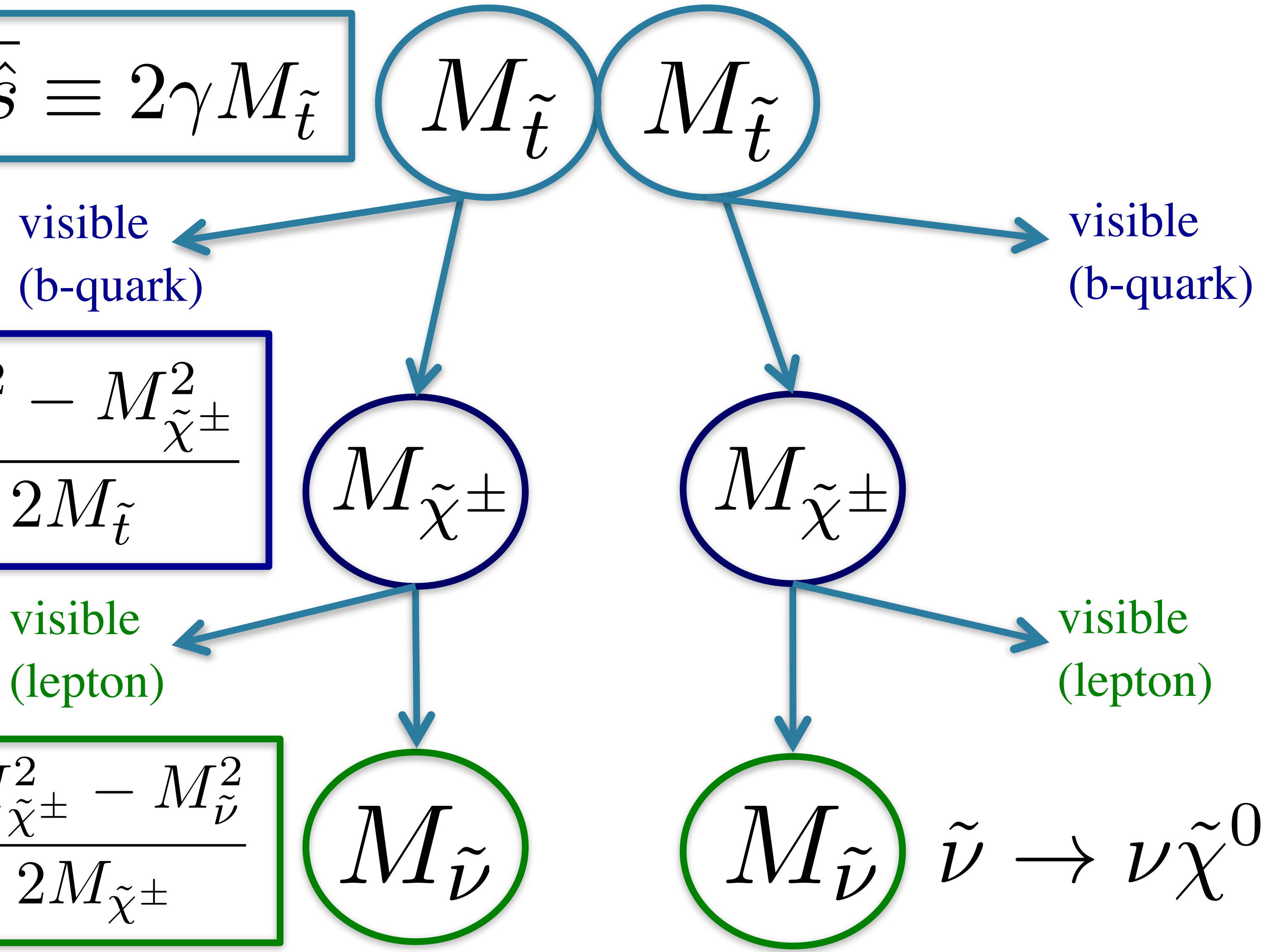


# di-leptonic top/stop topology

$$\sqrt{\hat{s}} \equiv 2\gamma M_{\tilde{t}}$$

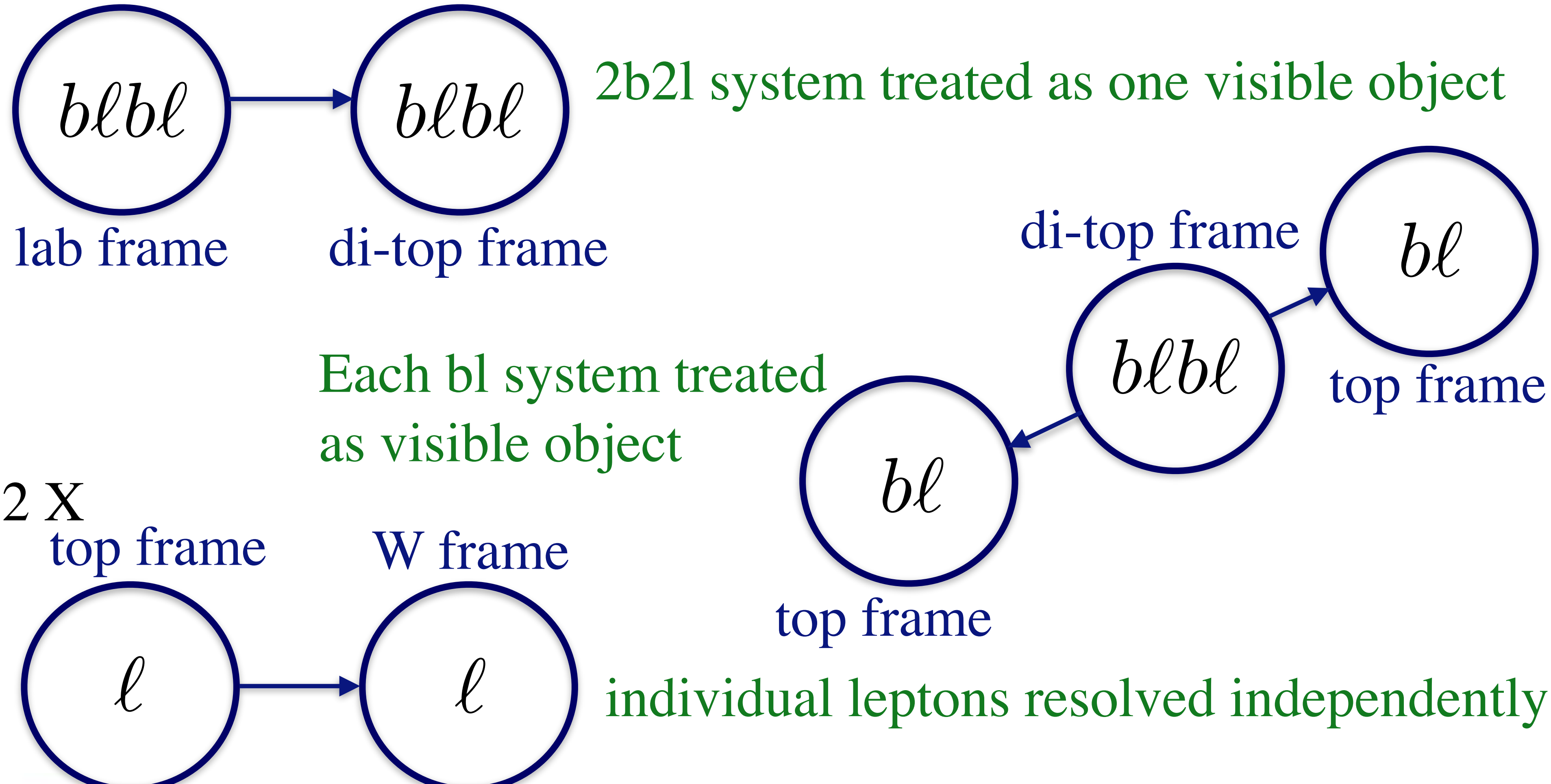
$$E_b \equiv \frac{M_{\tilde{t}}^2 - M_{\tilde{\chi}^\pm}^2}{2M_{\tilde{t}}}$$

$$E_{\rm lep} \equiv \frac{M_{\tilde{\chi}^\pm}^2 - M_{\tilde{\nu}}^2}{2M_{\tilde{\chi}^\pm}}$$

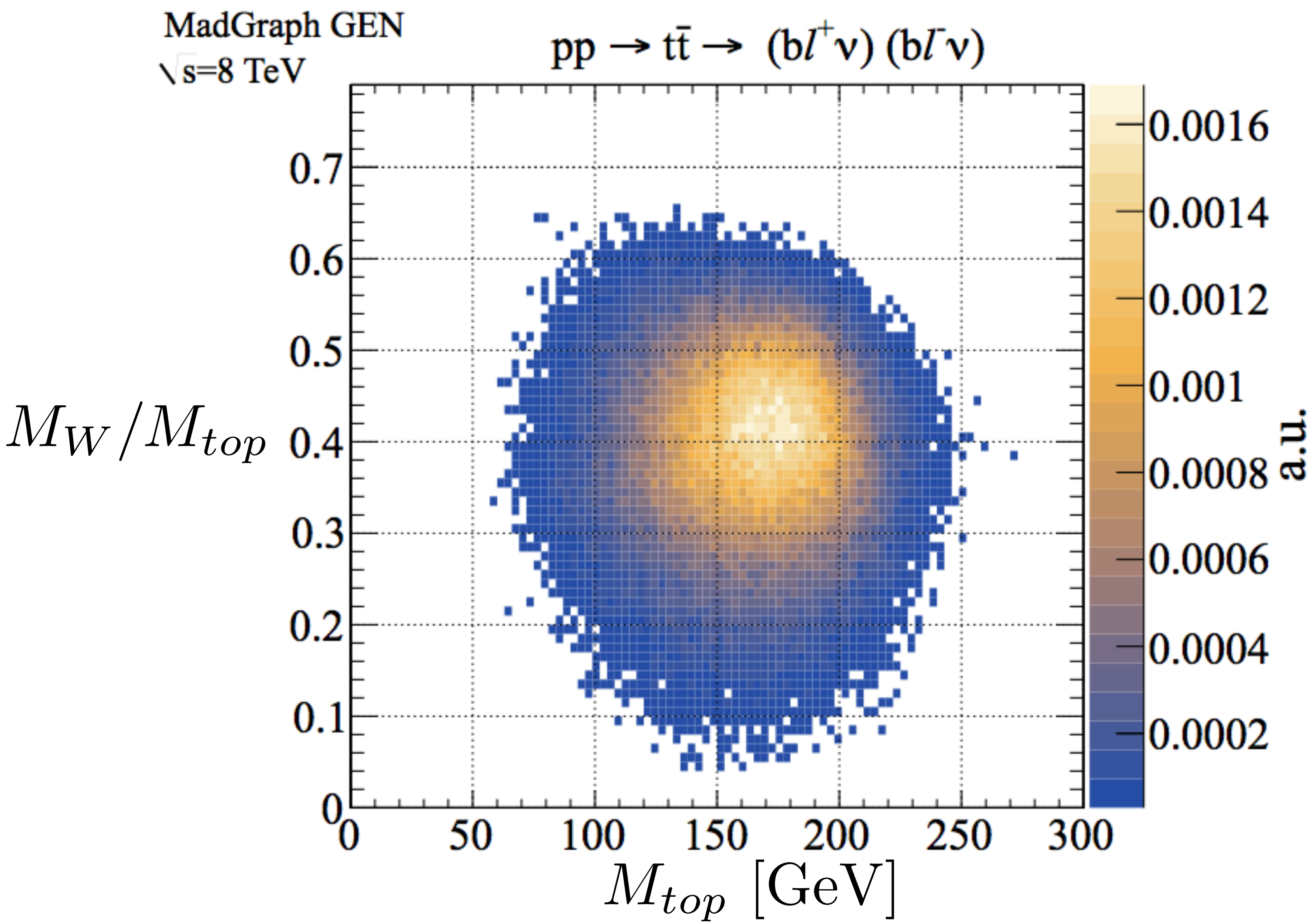


# Recursive Jigsaw Reconstruction

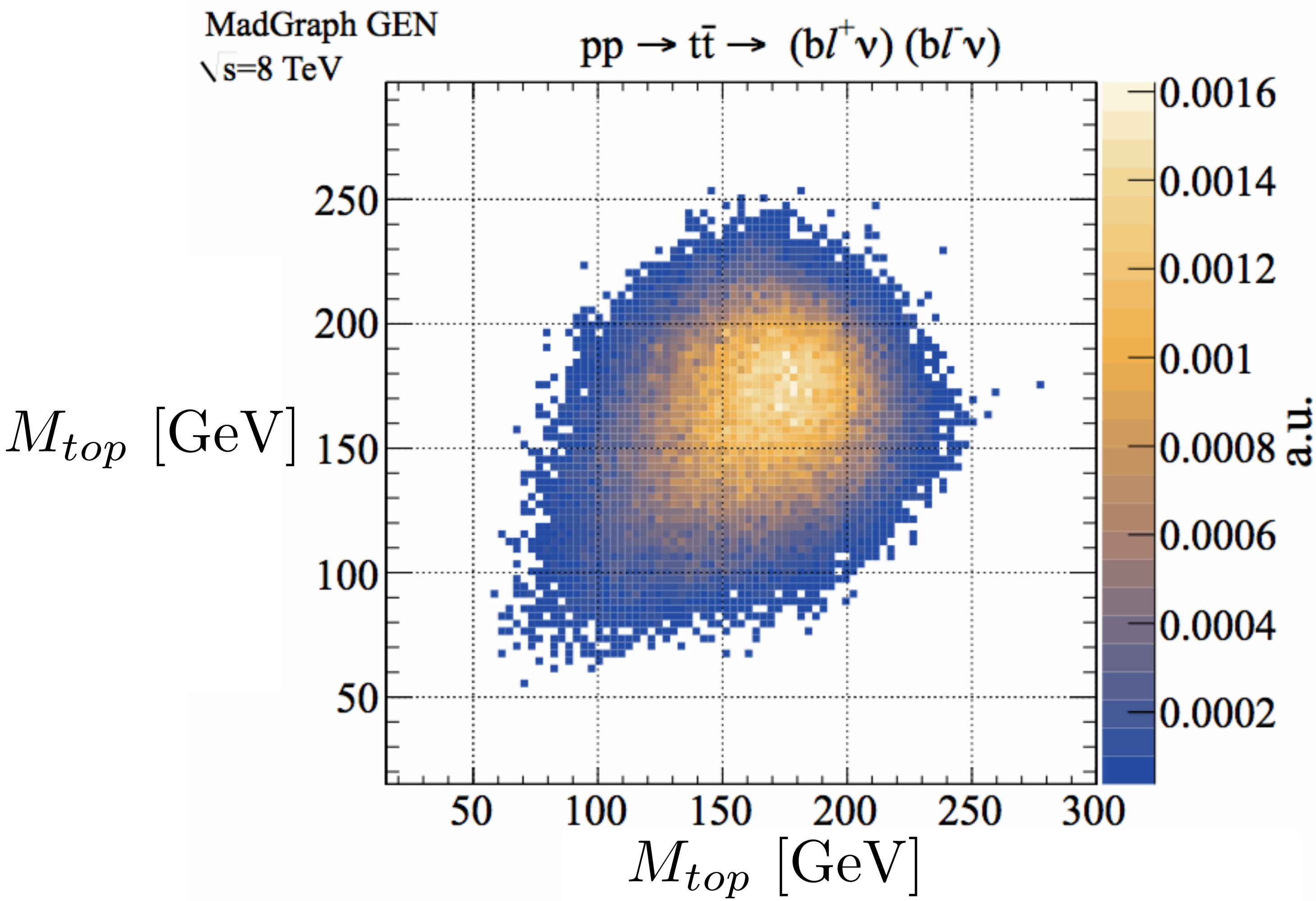
Move through each reference frame of interest in the event, specifying only d.o.f. relevant to each transformation:



# The Recursive Jigsaw Reconstruction




The scales can be extracted independently




In fact the scales can be extracted independently for each top – the reconstruction chains are ***decoupled***

$$\sqrt{\hat{s}}_R \equiv M_R,\ \vec{p}_R^{\,lab},\ \cos\theta_R$$

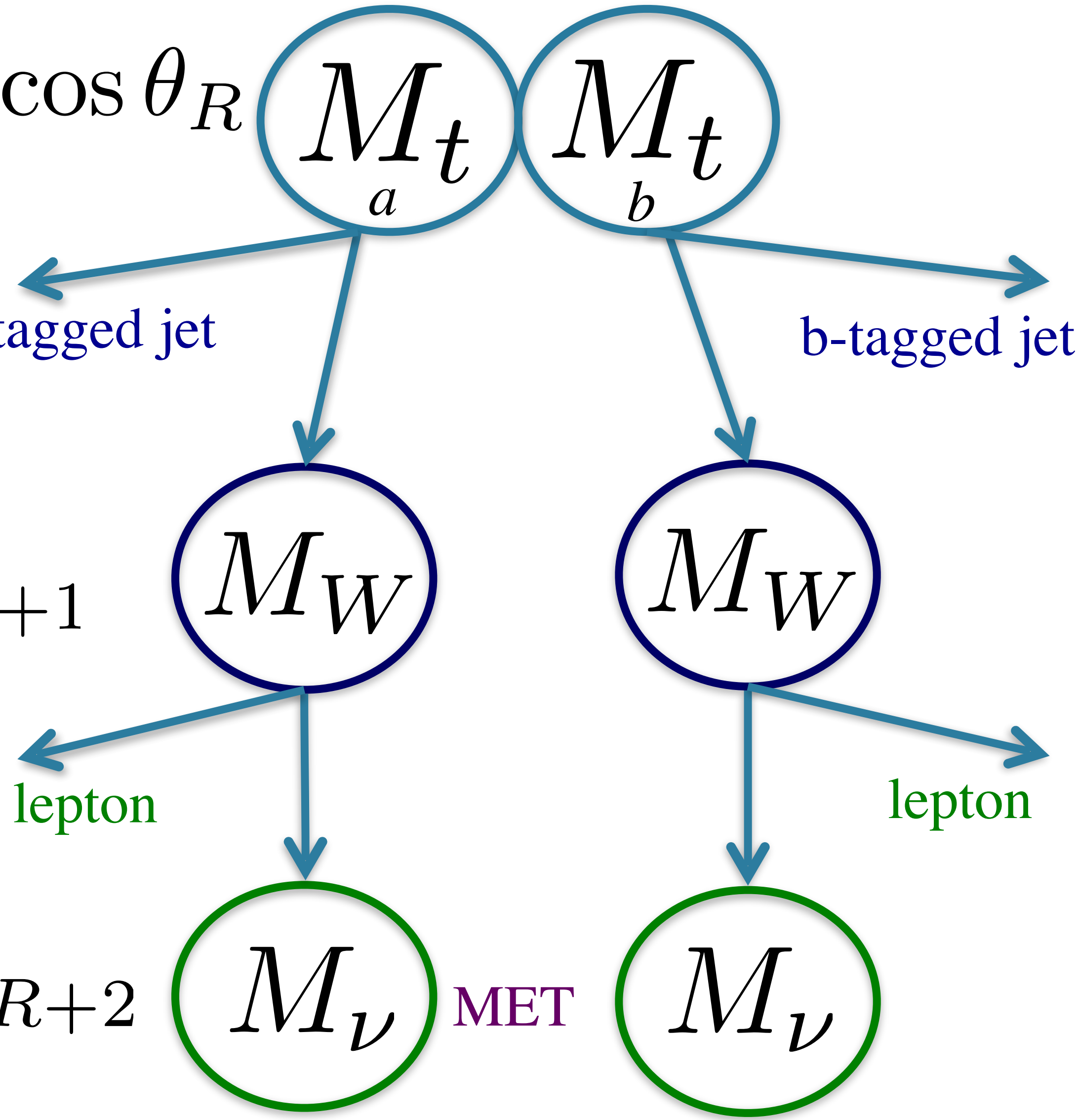
$$\Delta\phi_{R+1_a,R+1_b}$$

2 X

$$M_t \equiv M_{R+1}, \cos\theta_{R+1}$$

$$\Delta\phi_{R+1_a,R+2_a}$$

$$M_W \equiv M_{R+2}, \cos\theta_{R+2}$$



# The di-leptonic top basis

$$M_{t\bar{t}},\ \vec{p}_{t\bar{t}}, \cos\theta_{TT}$$

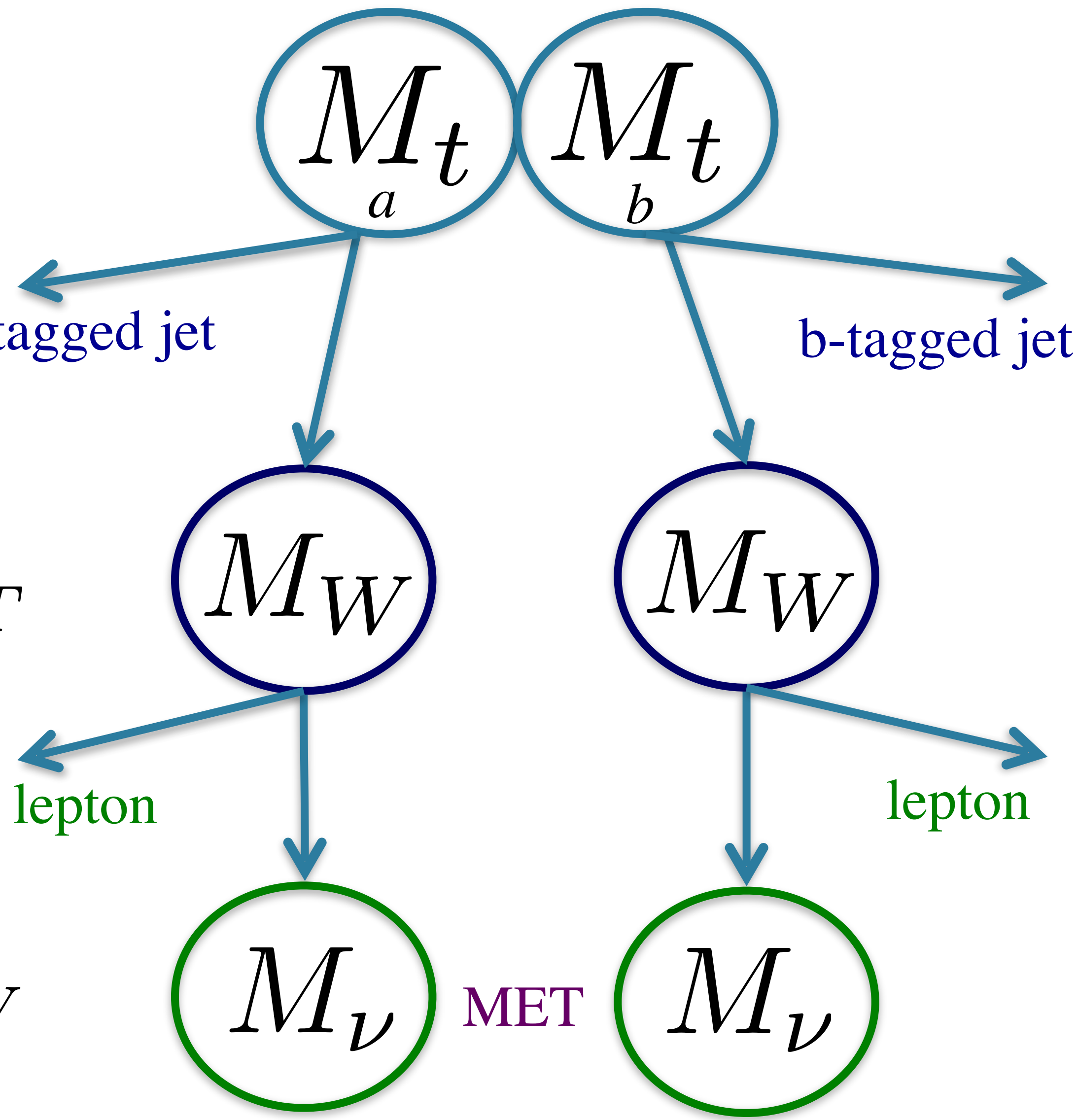
$$\Delta\phi_{T1,T2}$$

2 X

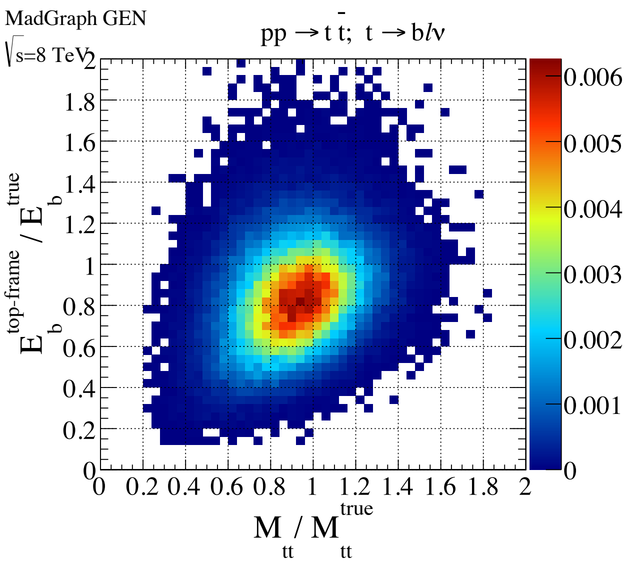
$$E_b^{\mathrm{top-frame}}, \cos\theta_T$$

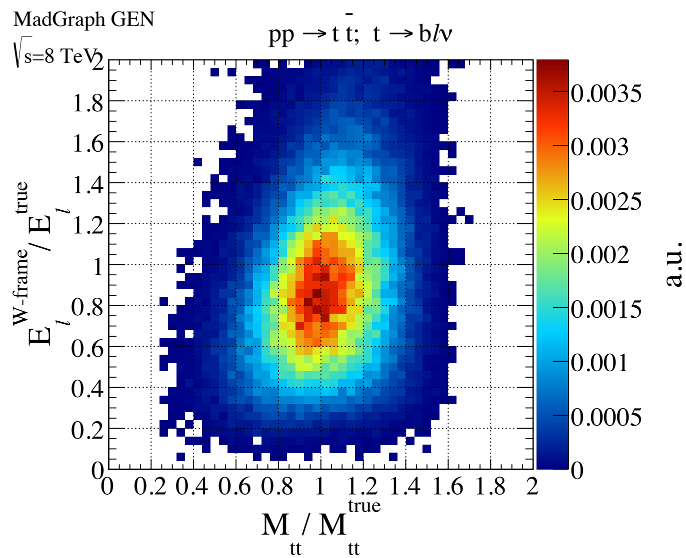
$$\Delta\phi_{T,W}$$

$$E_\ell^{\mathrm{W-frame}}, \cos\theta_W$$

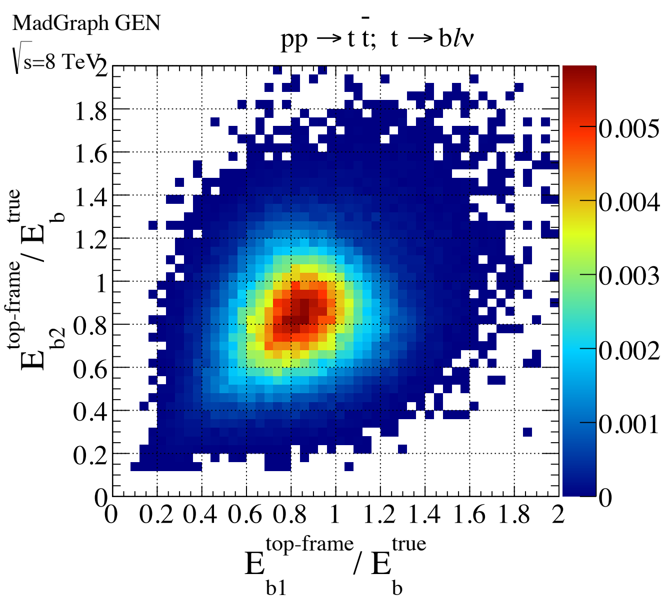


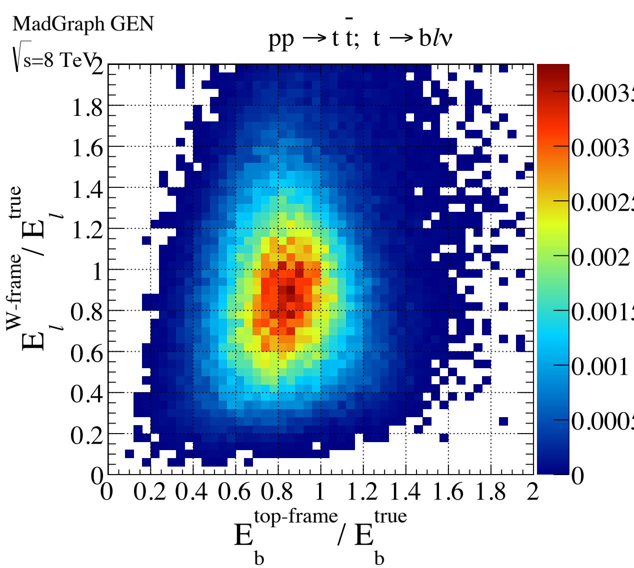
# The di-leptonic top basis

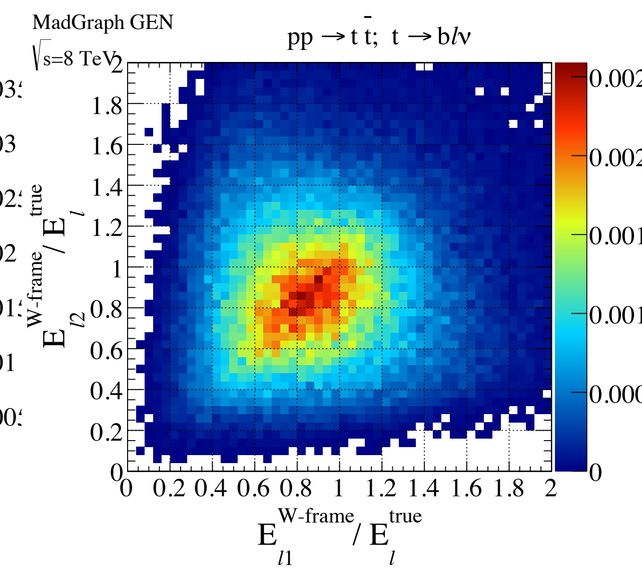


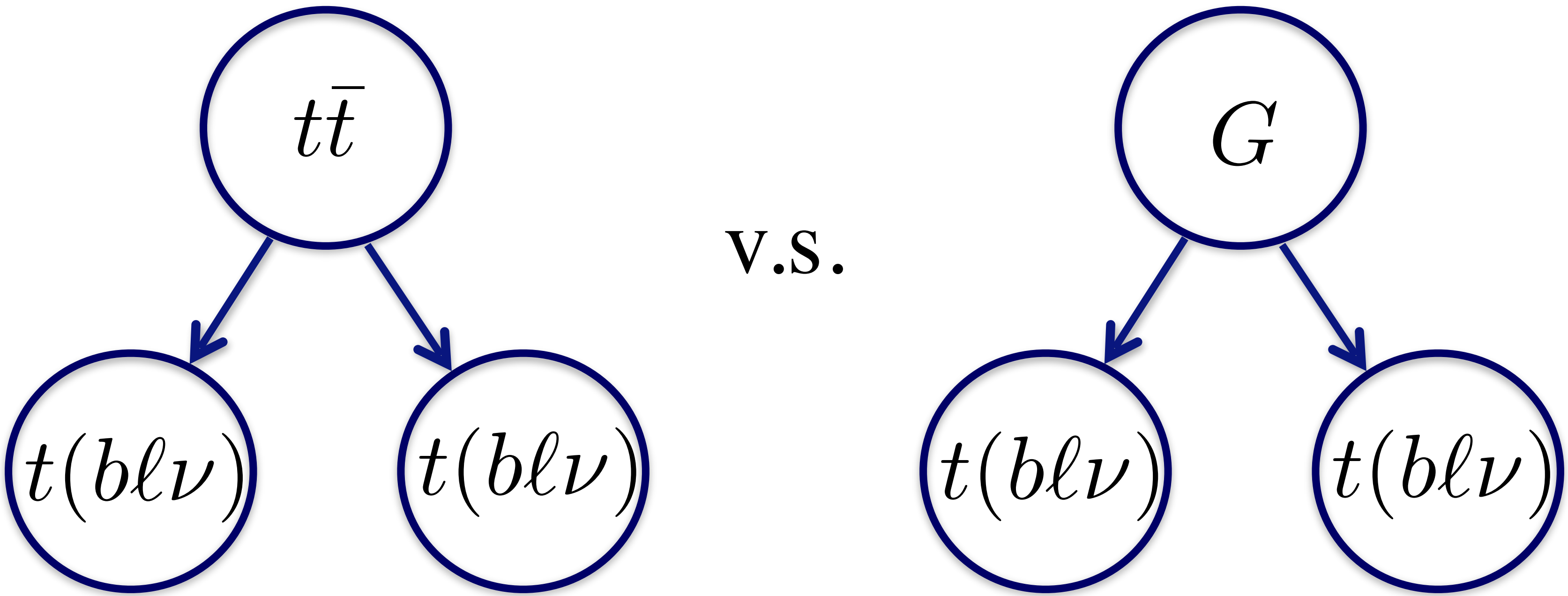

largely independent information about five different masses



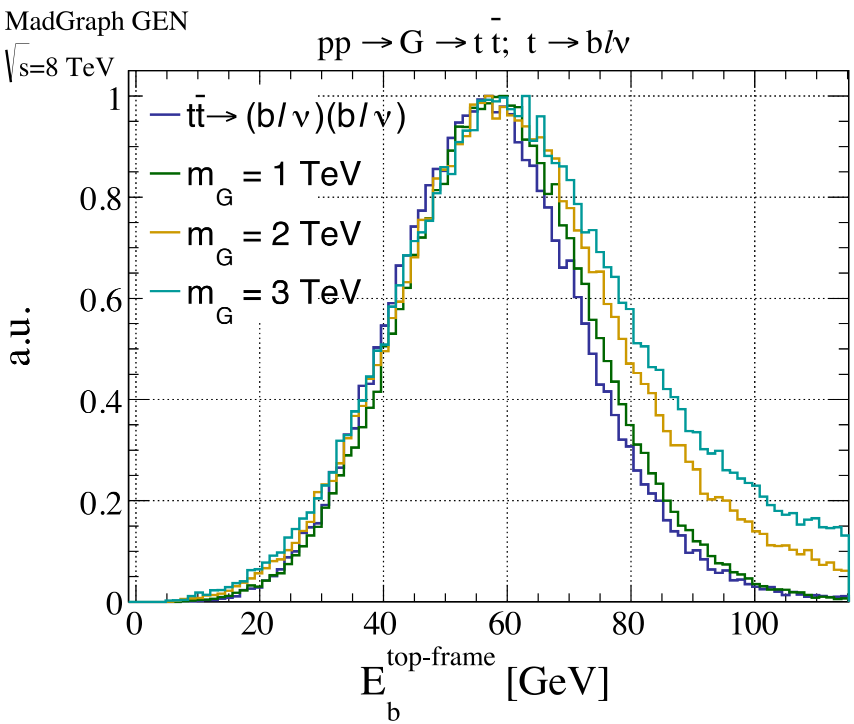
Different variables in the basis are useful for different signals

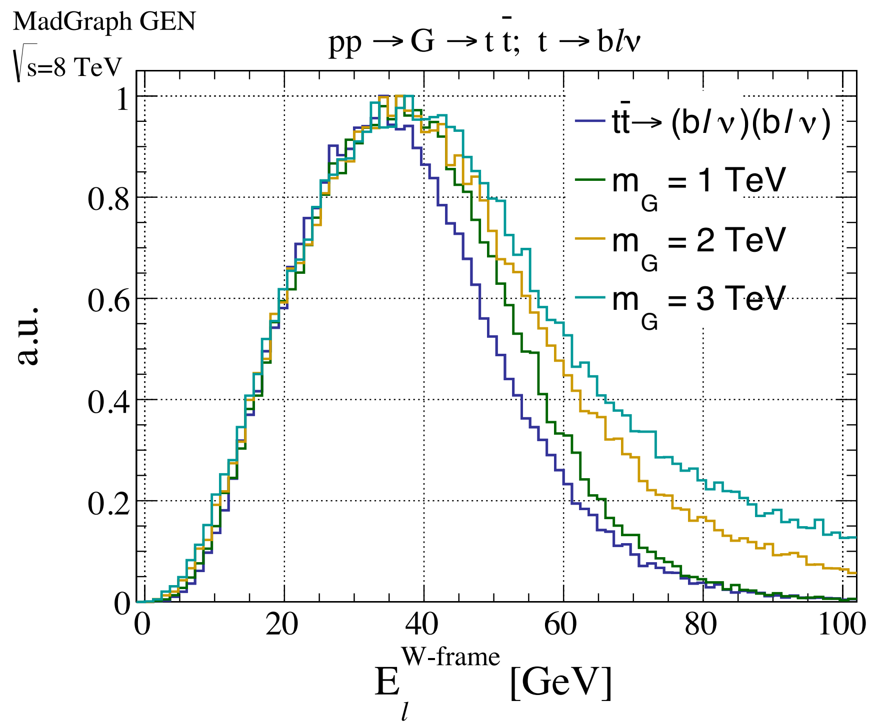



First, we consider resonant ttbar production through a graviton

# The di-leptonic top basis vs Gravitons

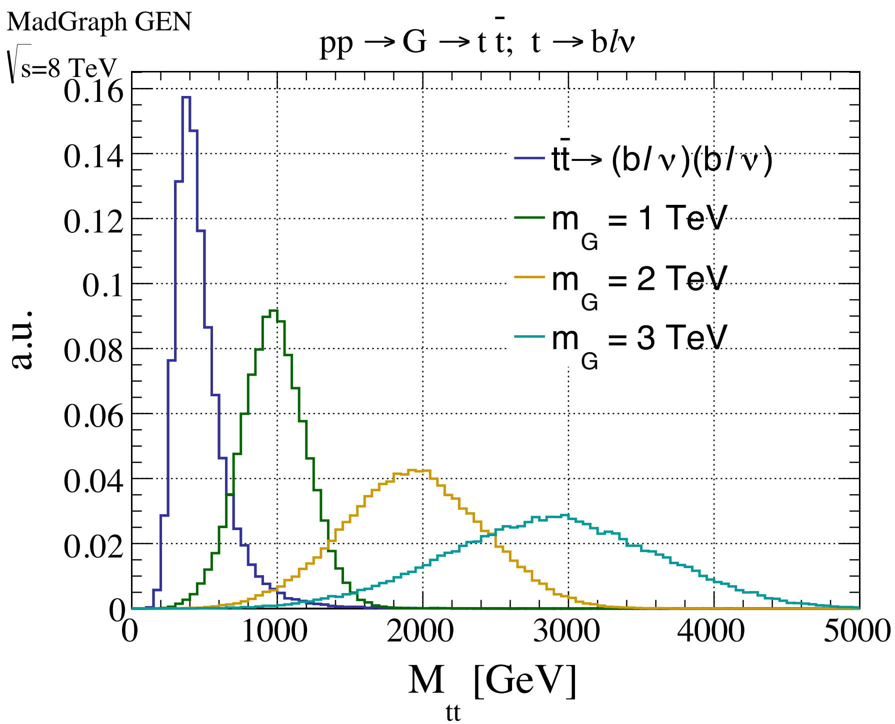
Different variables in the basis are useful for different signals

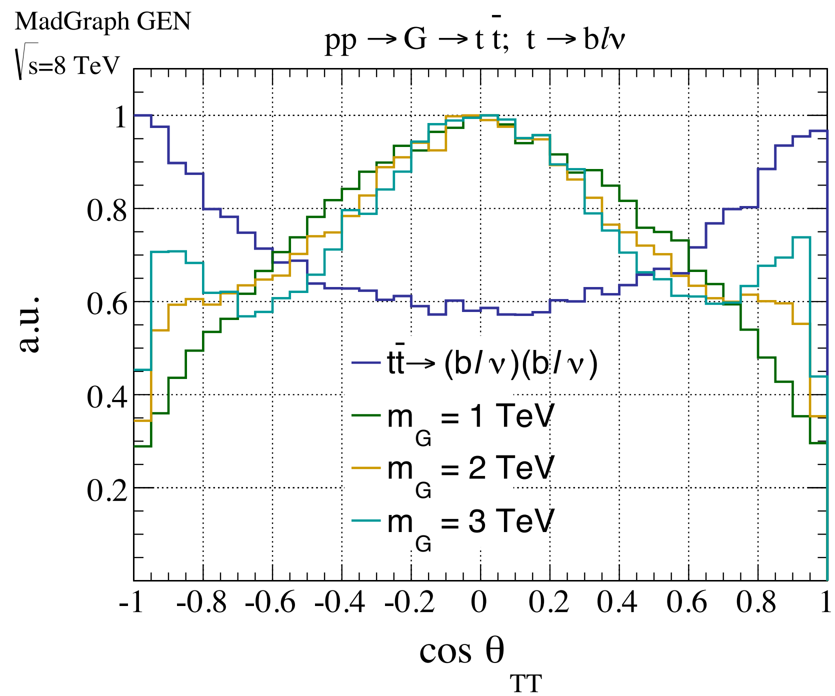



distributions of top/W/neutrino mass-splitting-sensitive observables are nearly identical since graviton signal and non-resonant background both contain on-shell tops

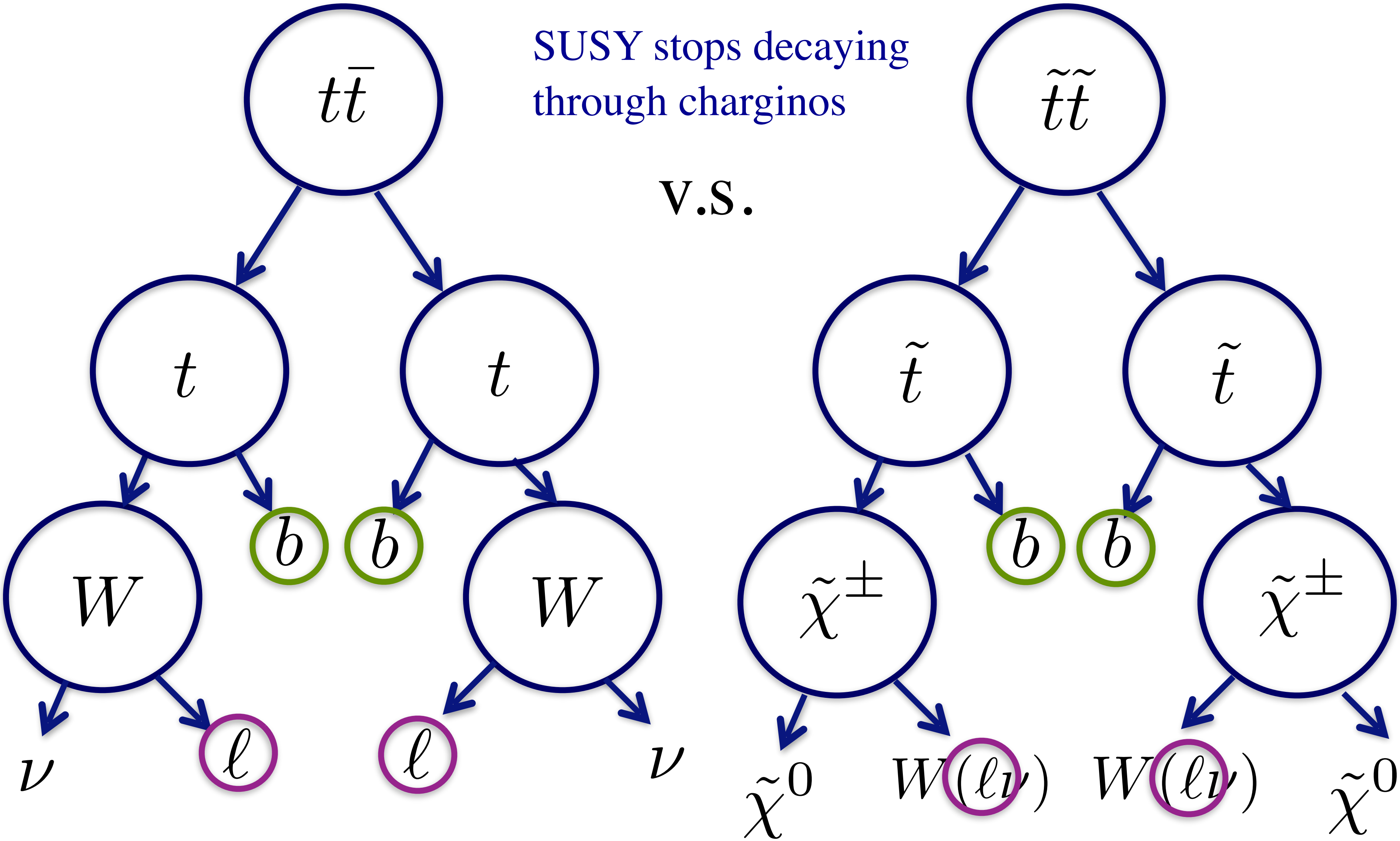
Different variables in the basis are useful for different signals




Instead, observables related to the production of the two tops are sensitive to the intermediate resonance

# The di-leptonic top basis vs Stops



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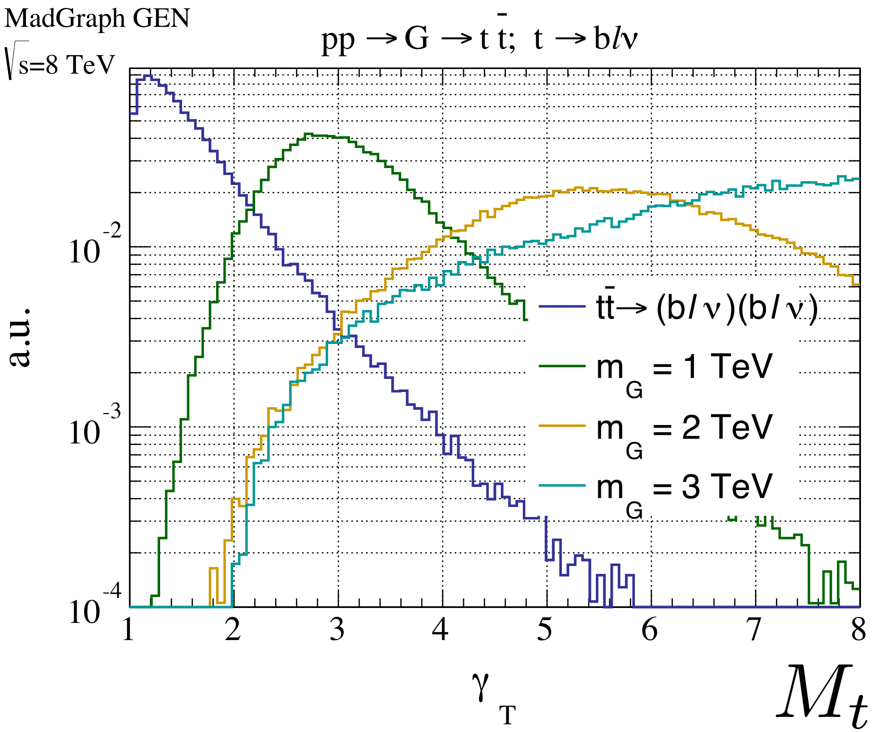
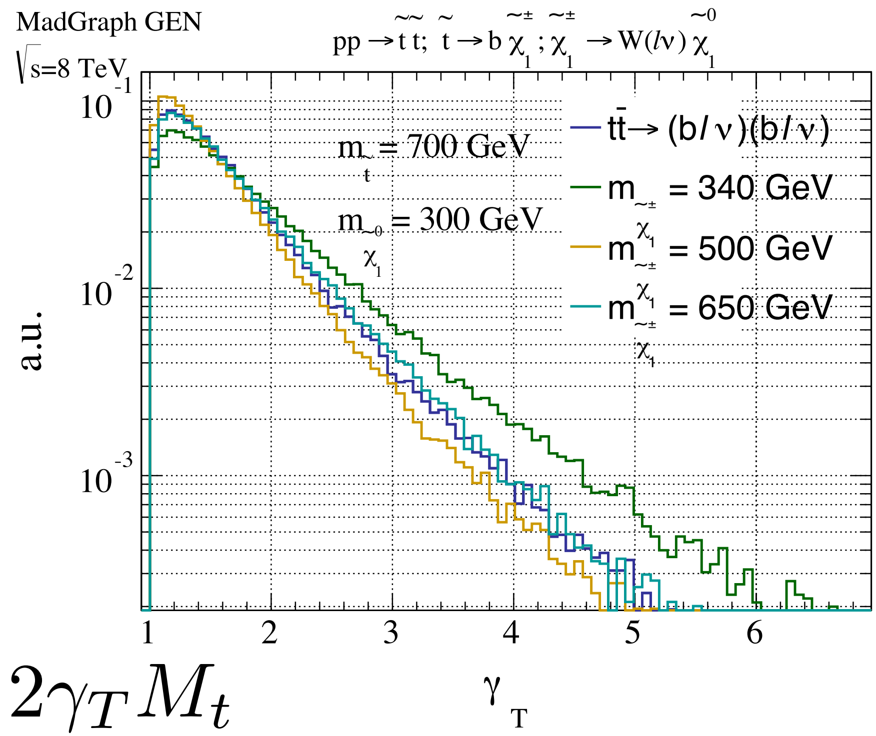
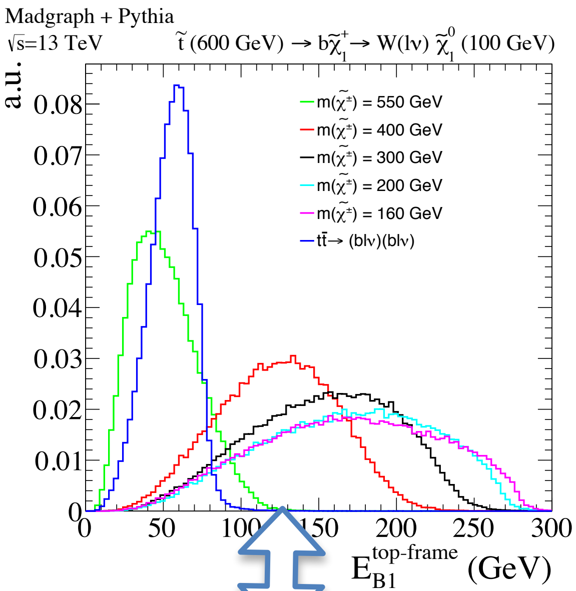


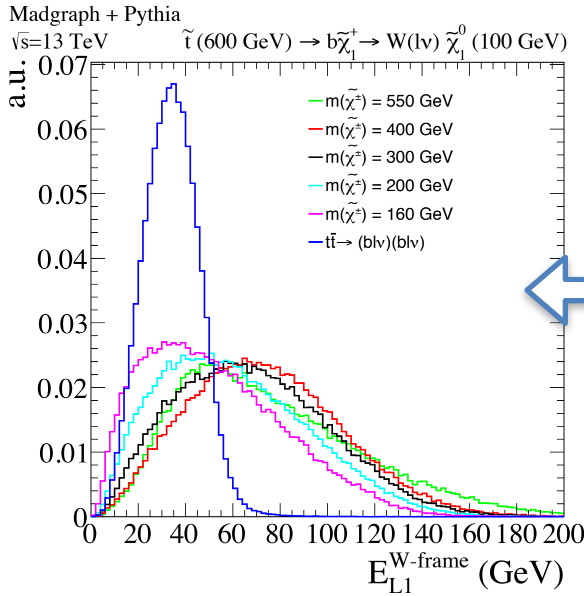



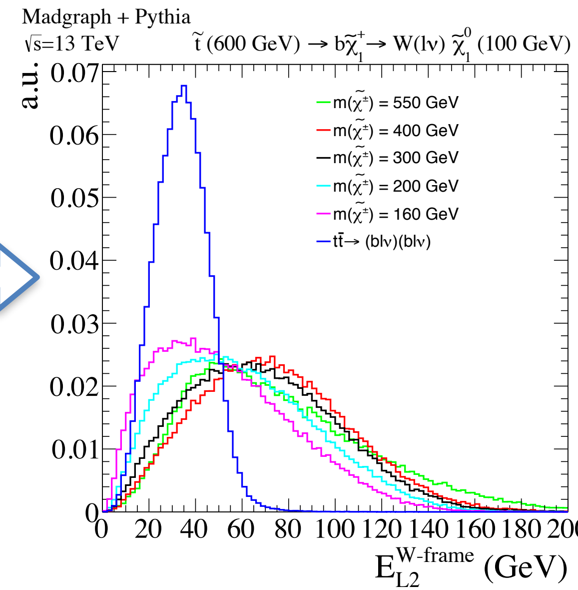

$$M_{tt} = 2\gamma_T M_t$$

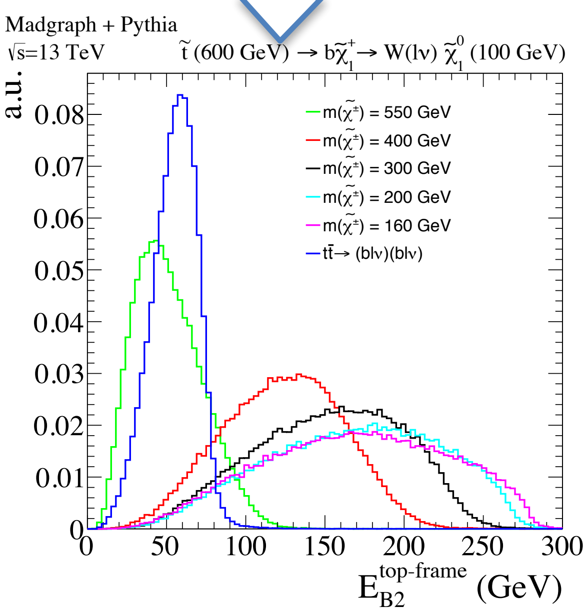
Observables sensitive to intermediate resonances cannot distinguish between non-resonant signals and background

# The di-leptonic top basis vs Stops



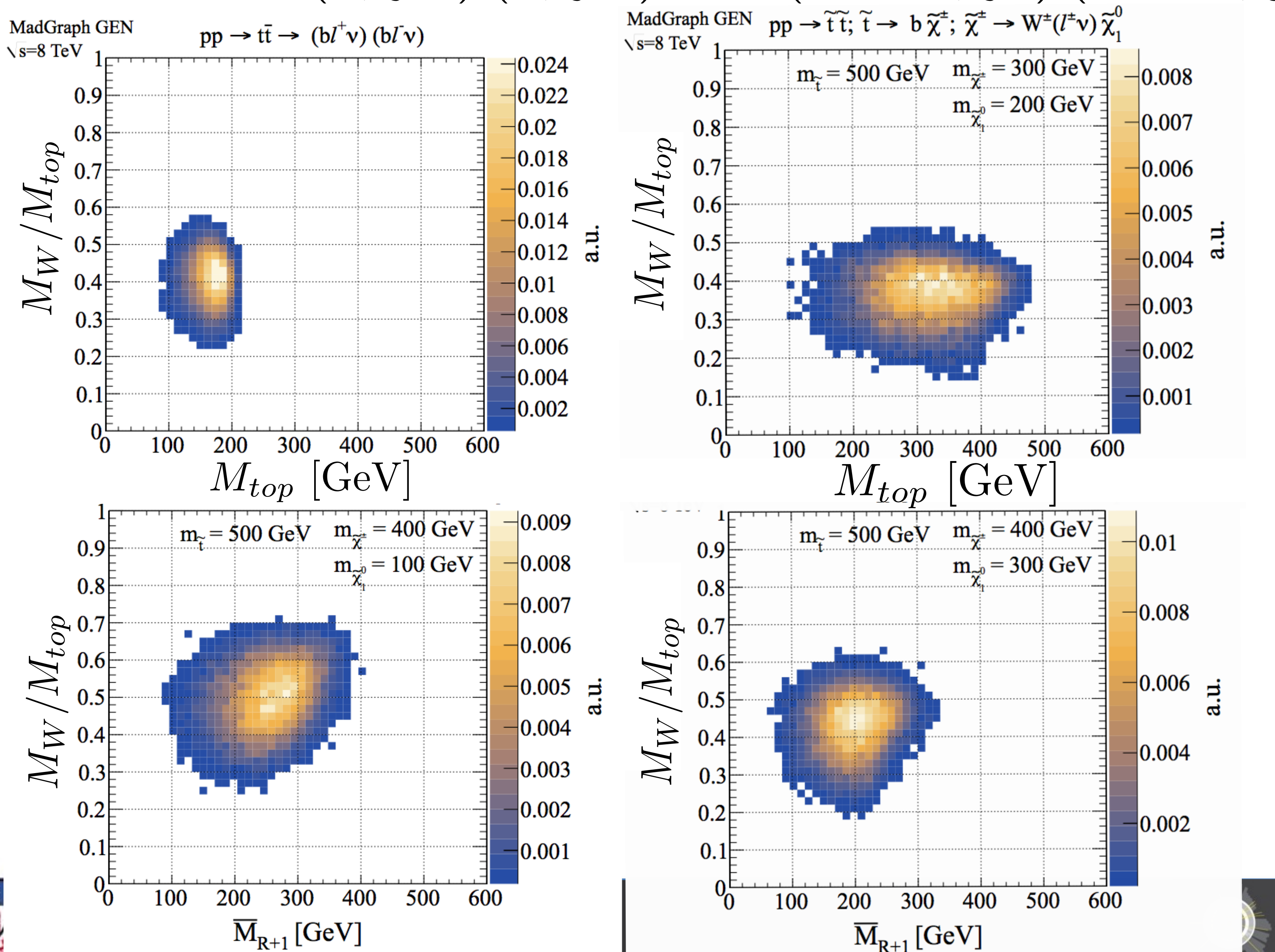




Mass-splitting-sensitive observables can be used to distinguish presence of signals.

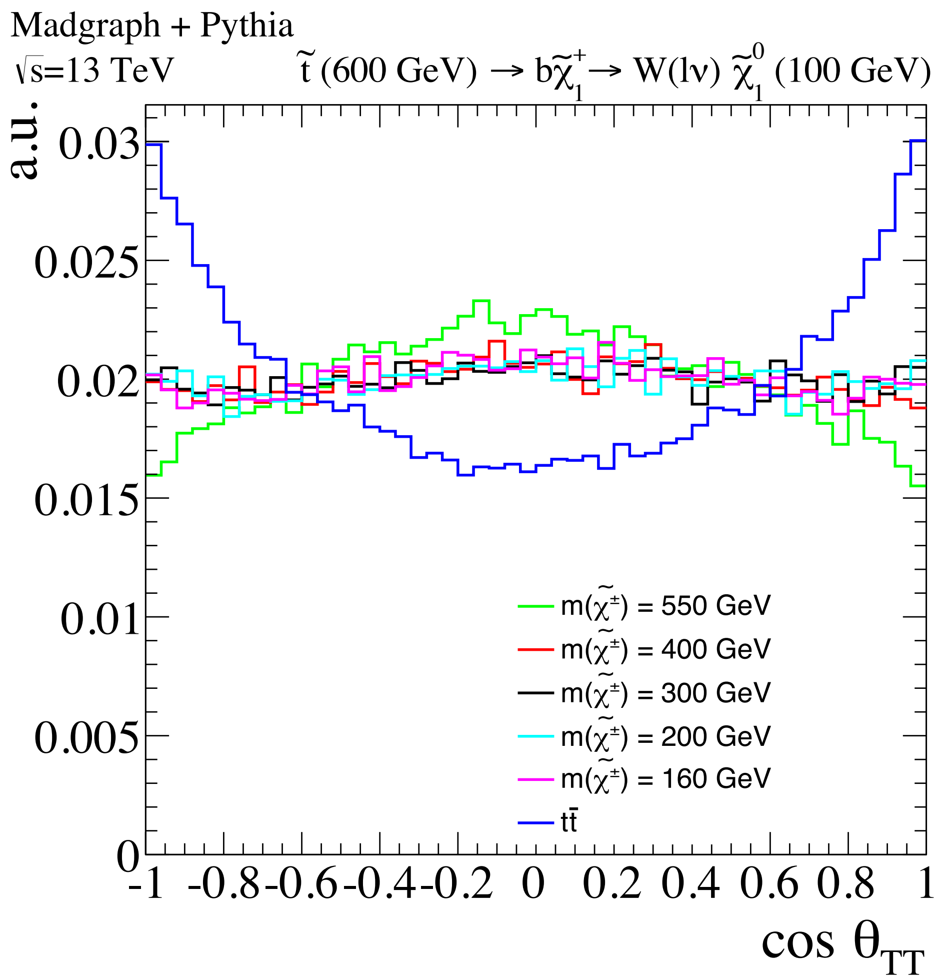
With variables for each hemisphere

# $t\bar{t} \to (b\ell\nu)(b\ell\nu)$ vs. $\tilde{t}\tilde{t} \to (b\tilde{\chi}^{\pm})(b\tilde{\chi}^{\pm}) \to (b\ell^{\pm}\nu\tilde{\chi}^{0})(b\ell^{\pm}\nu\tilde{\chi}^{0})$



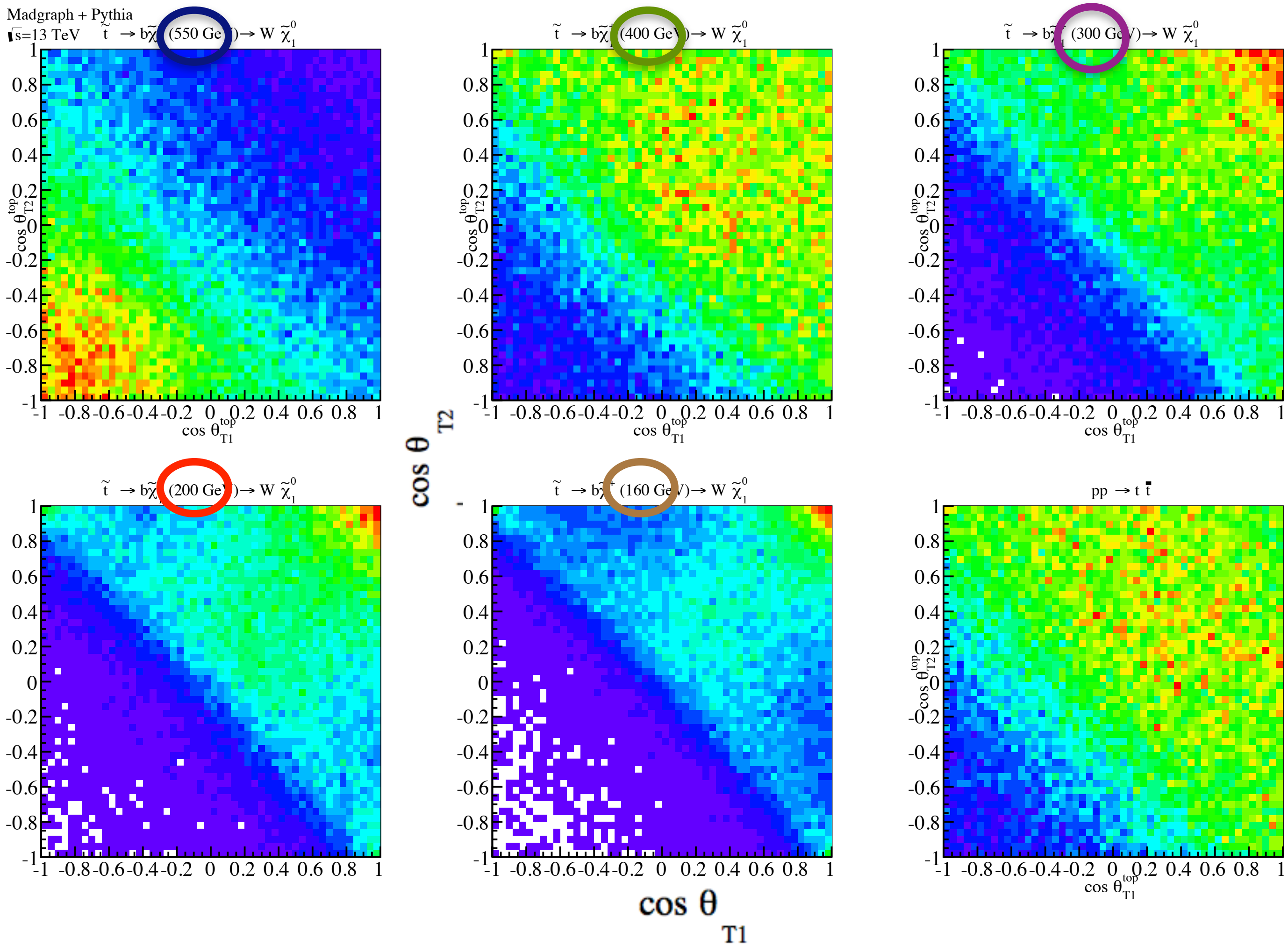

Multi-dimensional bump-hunting

# The di-leptonic top basis vs Stops




Decay angles are also sensitive to differences between stop signals and ttbar background

# The di-leptonic top basis vs Stops



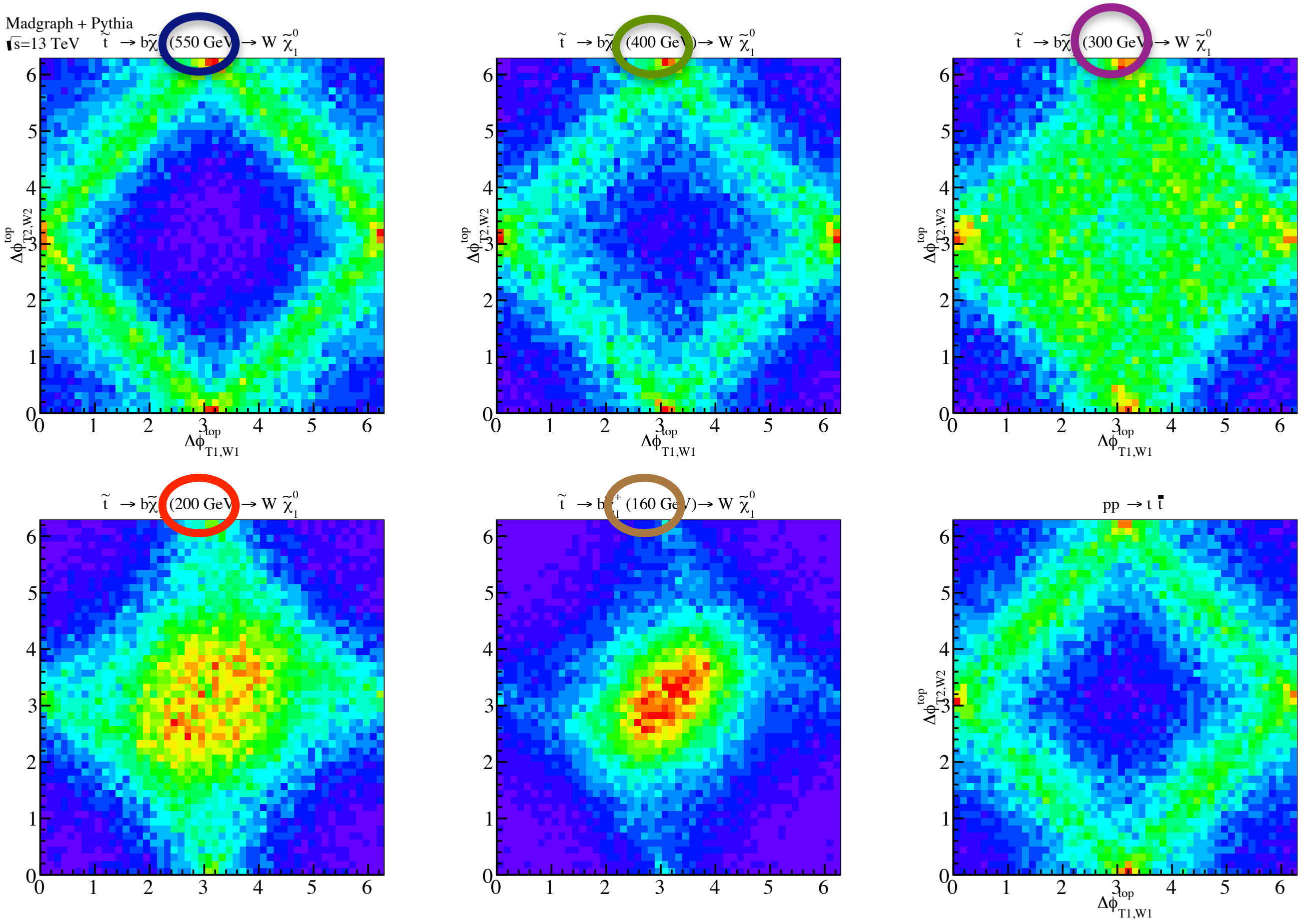

$m_{\tilde{t}_1} = 600 \text{ GeV}$

$m_{\tilde{\chi}^\pm} =$ 550, 400, 300, 200, 160 GeV

$m_{\tilde{\chi}^0_1} = 100 \text{ GeV}$

Decay angles are also sensitive to differences between stop signals and ttbar background

# The di-leptonic top basis vs Stops




$$m_{\tilde{t}_1} = 600 \text{ GeV}$$

$$m_{\tilde{\chi}^{\pm}} = \begin{matrix} 550 \\ 400 \\ 300 \\ 200 \\ 160 \end{matrix} \text{ GeV}$$

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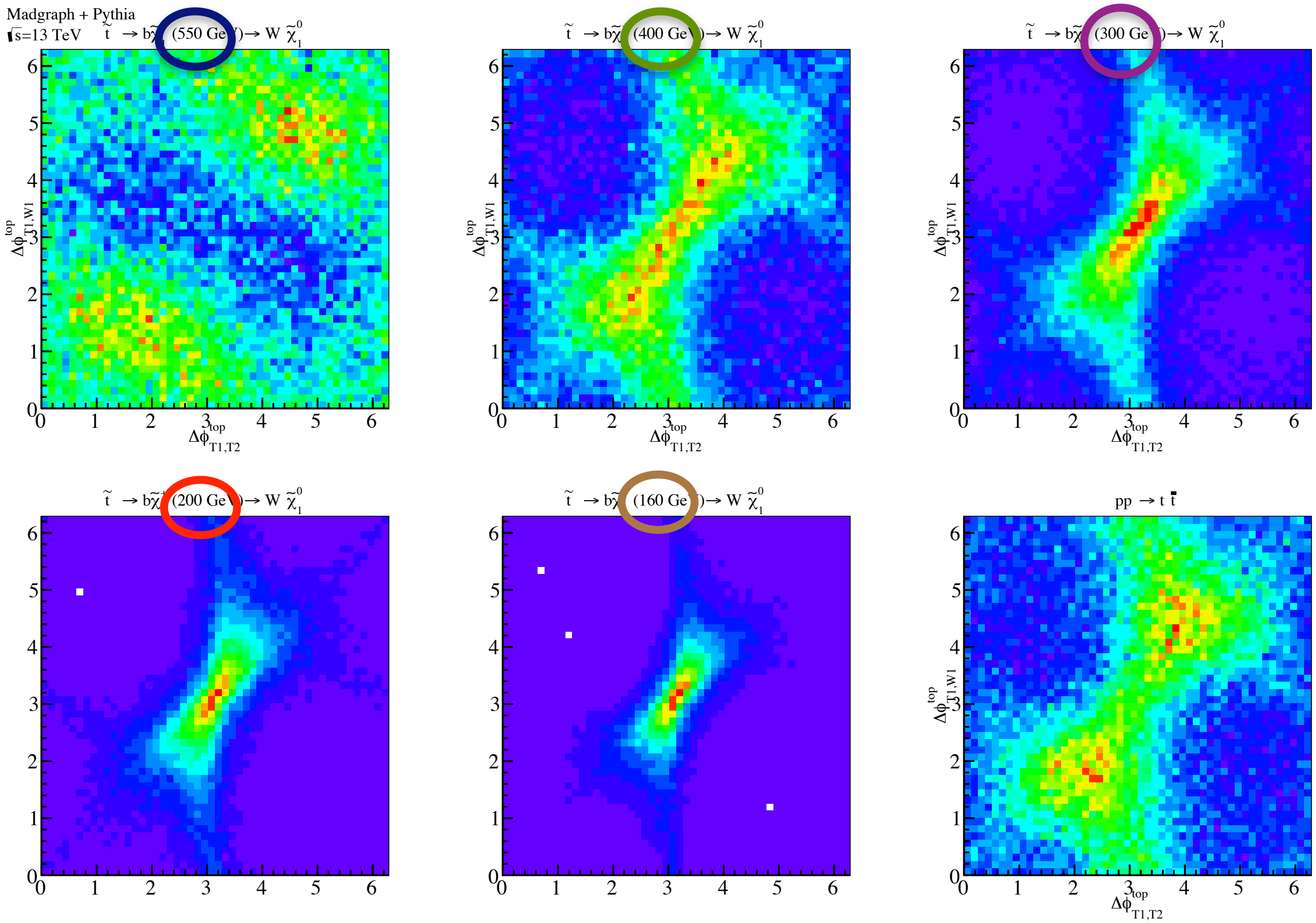
The azimuthal angle between the the top and W decay planes $\Delta\phi_{T1,W1}$ from each hemisphere $\Delta\phi_{T2,W2}$

# The di-leptonic top basis vs Stops




$$m_{\tilde{t}_1} = 600 \text{ GeV}$$

$$m_{\tilde{\chi}^\pm} = 550,\ 400,\ 300,\ 200,\ 160 \text{ GeV}$$

$$m_{\tilde{\chi}^0_1} = 100 \text{ GeV}$$

The azimuthal angle between the the top and W decay planes $\Delta\phi_{T1,W1}$
and the angle between the two top decay planes $\Delta\phi_{T1,T2}$

# Summary

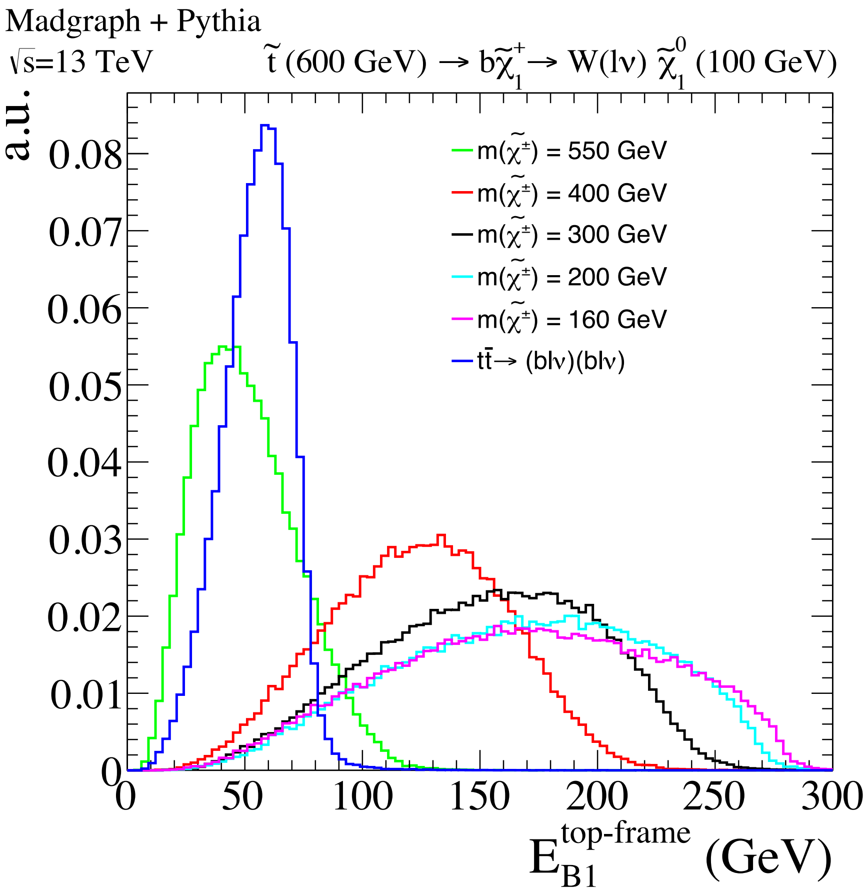
- The strategy is to not only develop 'good' mass estimator variables, but to decompose each event into a ***basis of kinematic variables***
- Through the recursive procedure, each variable is (as much as possible) ***independent of the others***
- The interpretation of variables is straightforward; they each correspond to an ***actual, well-defined, quantity in the event***
- For more complicated topologies (like di-leptonic top) the two hemispheres are ***largely decoupled***, i.e., ***the decay chains can be reconstructed independently*** ➔ no need to assume/require symmetry between the heavy particle decays (appealing method to interrogate mixed decays)
- Work to be summarised in arXiV:1408.xxx

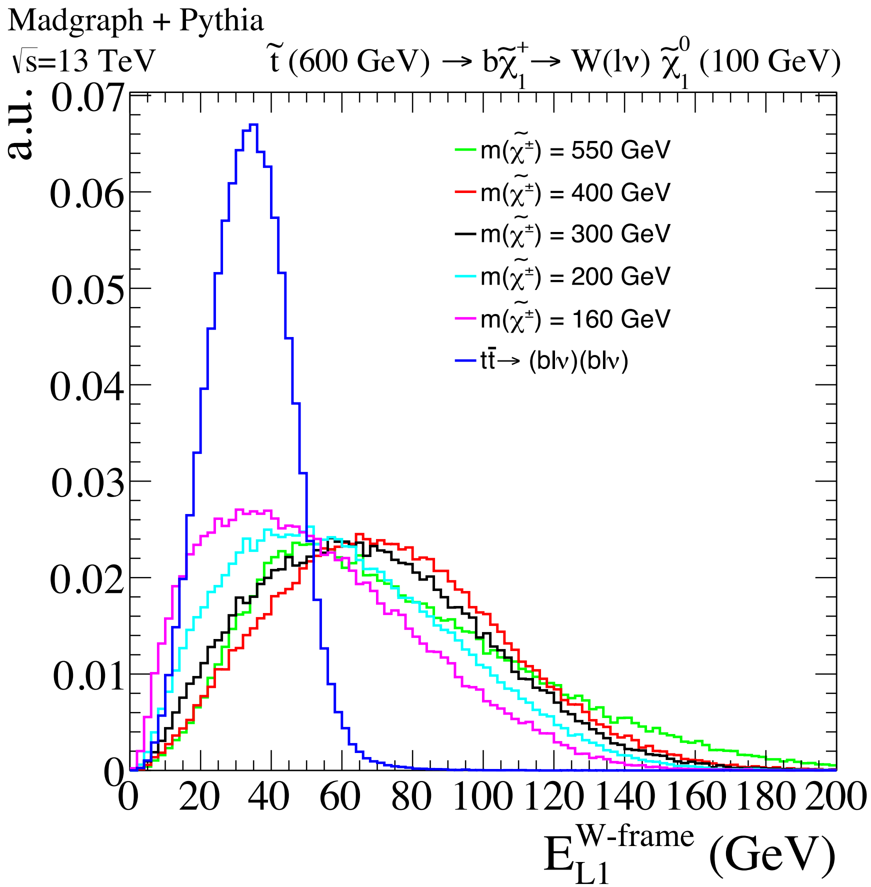
# Extras

Harvard Club of Australia
FOUNDATION

ARC Centre of Excellence for Particle Physics at the Terascale

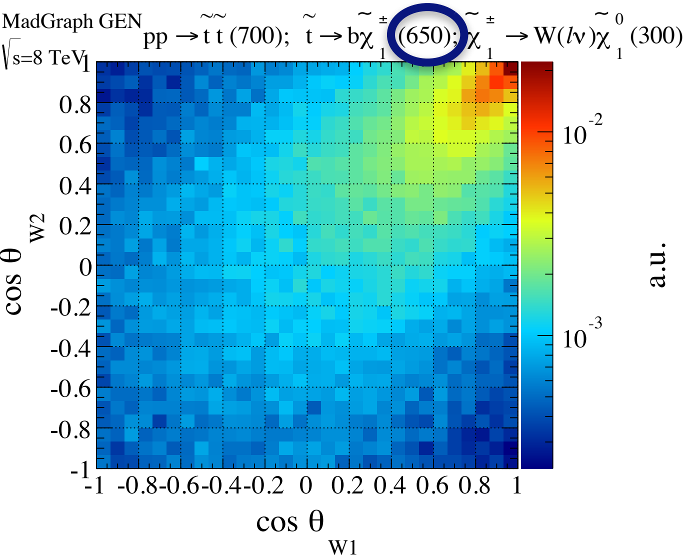
# The di-leptonic top basis vs Stops

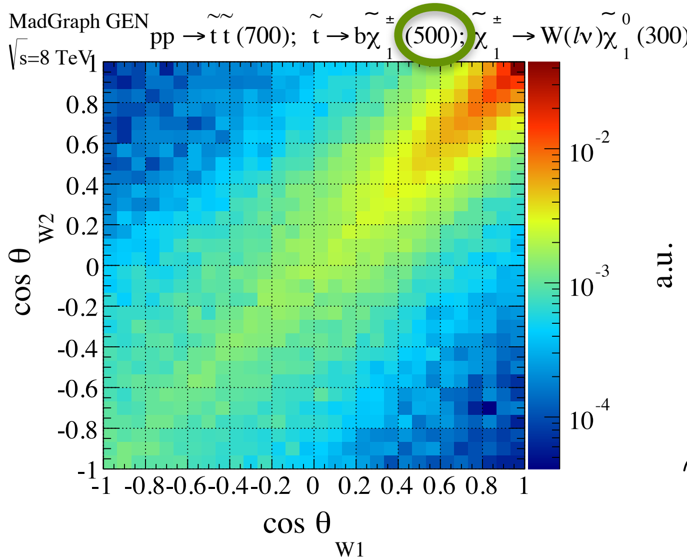



Mass-splitting-sensitive observables can be used to distinguish presence of signals

# The di-leptonic top basis vs Stops

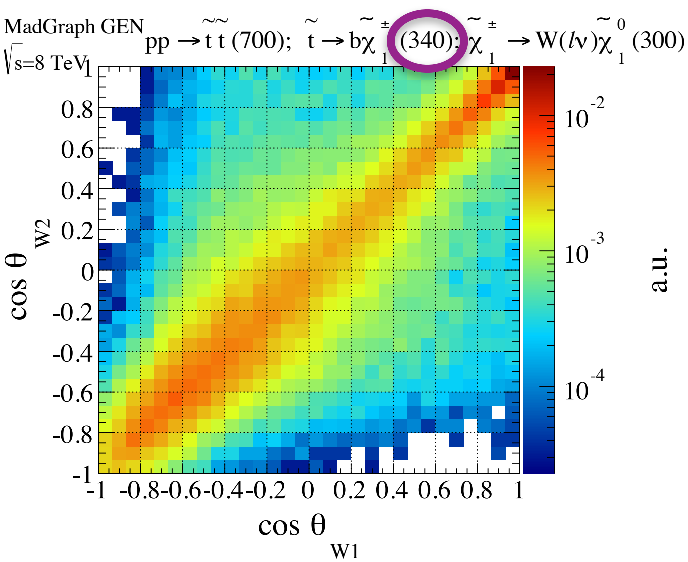


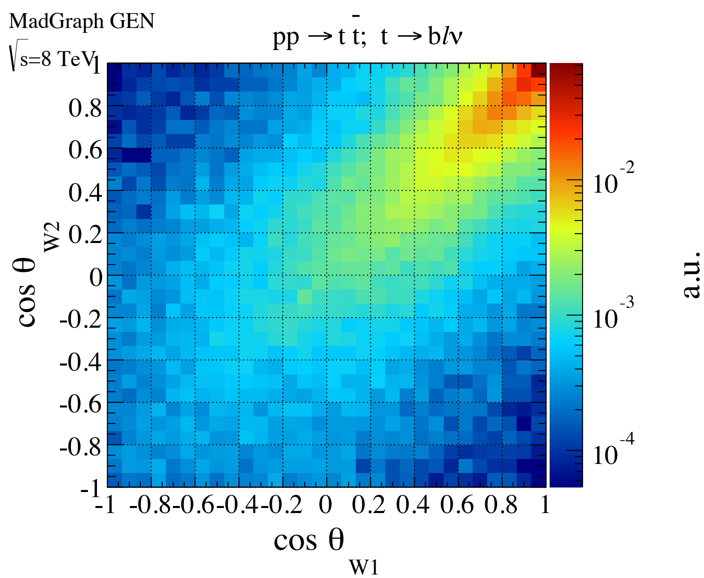




$$m_{\tilde{t}} = 700\ \text{GeV}$$

$$n_{\tilde{\chi}^{\pm}} = \begin{matrix} 650 \\ 500 \\ 340 \end{matrix}\ \text{GeV}$$

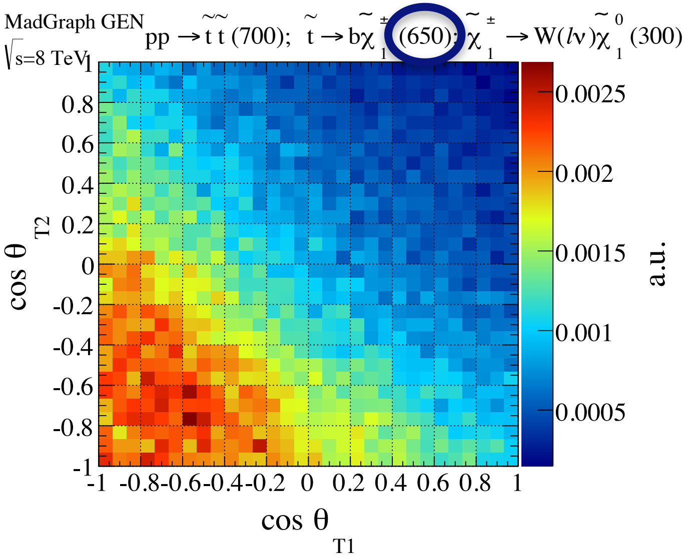
$$m_{\tilde{\chi}^0_1} = 300\ \text{GeV}$$

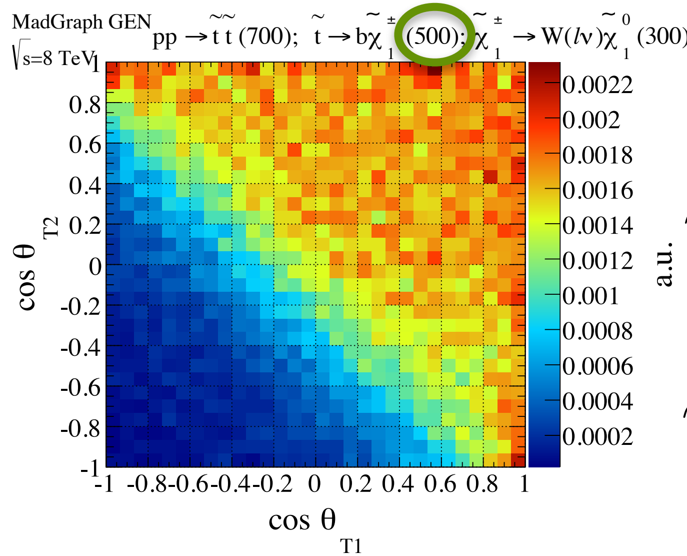



Decay angles are also sensitive to differences between stop signals and ttbar background

# The di-leptonic top basis vs Stops

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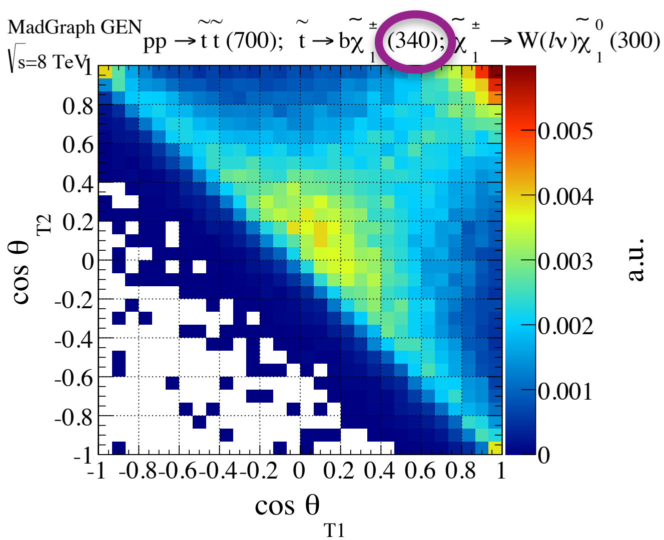
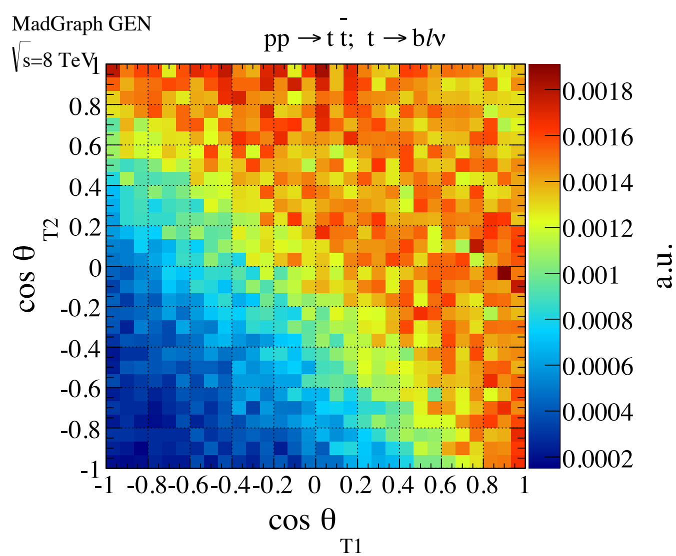
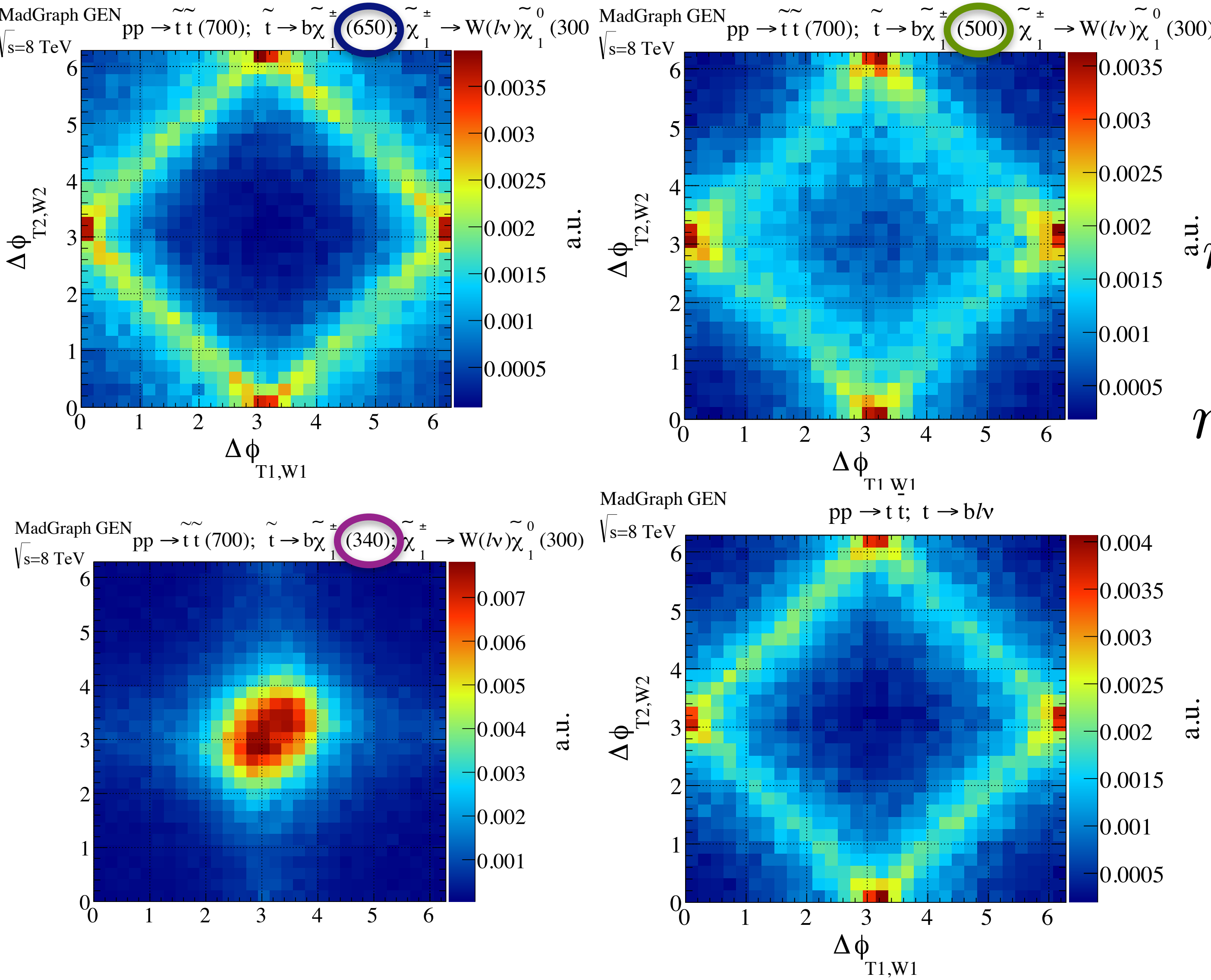



Decay angles are also sensitive to differences between stop signals and ttbar background

# The di-leptonic top basis vs Stops



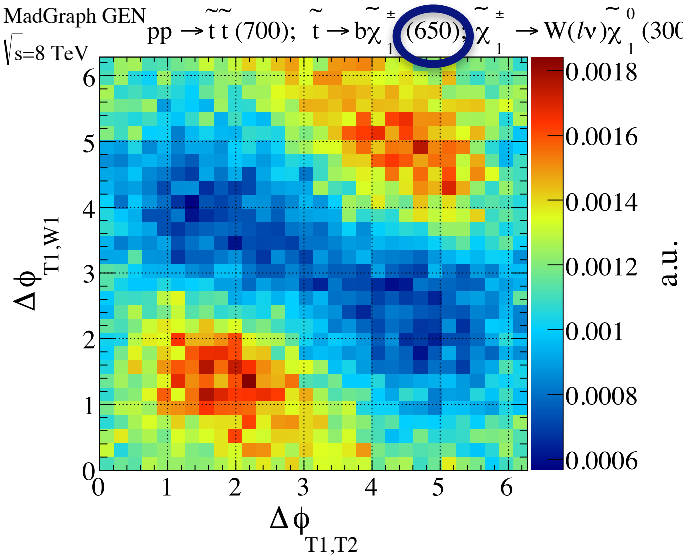

$$m_{\tilde{t}} = 700 \text{ GeV}$$

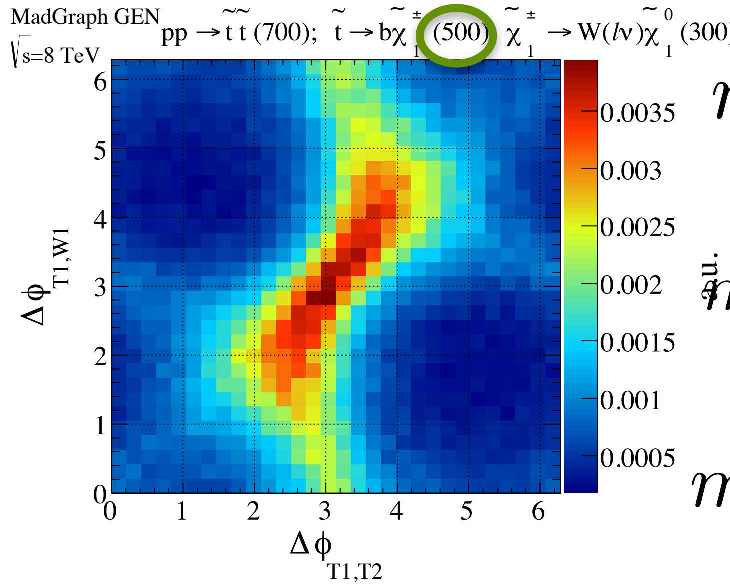
$$m_{\tilde{\chi}^{\pm}} = \begin{matrix} 650 \\ 500 \\ 340 \end{matrix} \text{ GeV}$$

$$m_{\tilde{\chi}_1^0} = 300 \text{ GeV}$$

The azimuthal angle between the the top and W decay planes from each hemisphere

# The di-leptonic top basis vs Stops




$$m_{\tilde{t}} = 700 \text{ GeV}$$

$$m_{\tilde{\chi}^{\pm}} = \begin{matrix} 650 \\ 500 \\ 340 \end{matrix} \text{ GeV}$$

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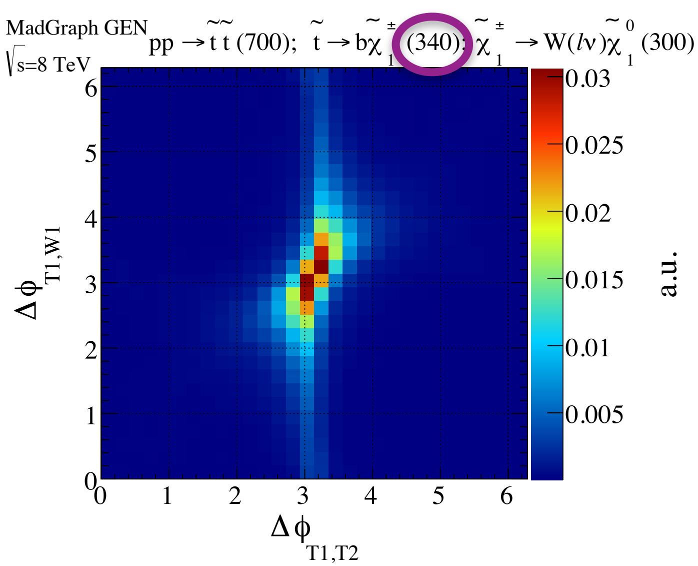
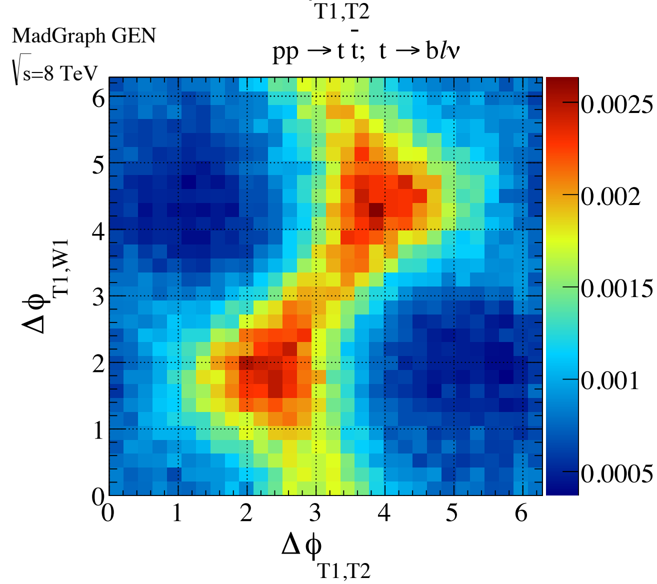
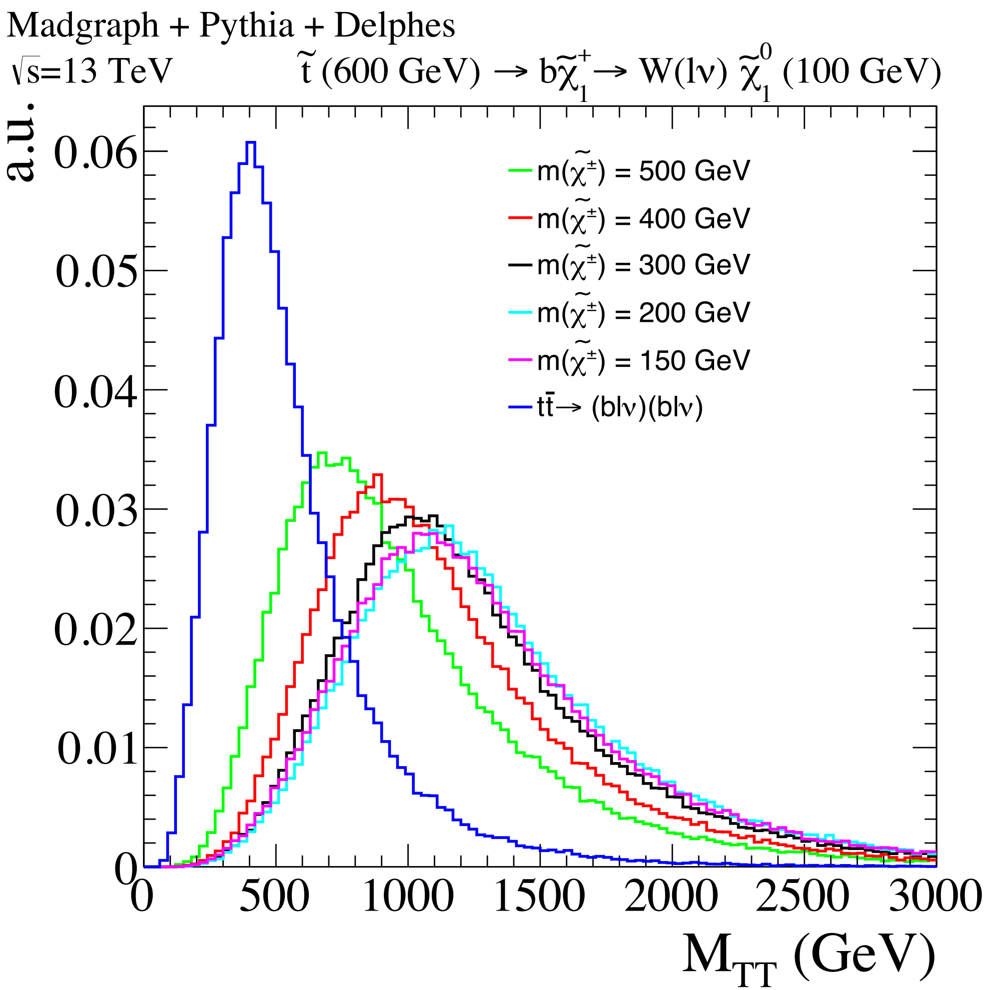


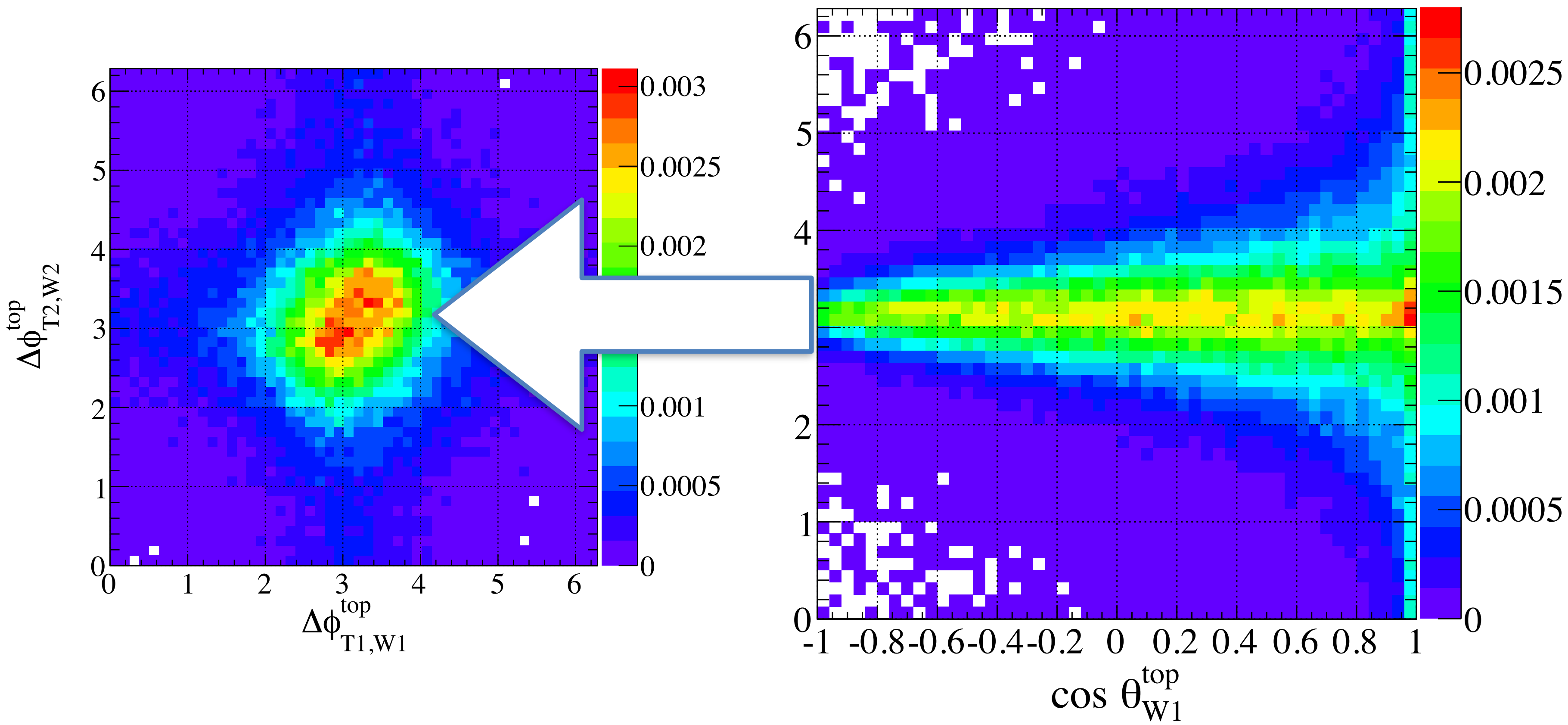




Here, the azimuthal angle between the the top and W decay planes $\Delta\phi_{T1,W1}$ and the angle between the two top decay planes $\Delta\phi_{T1,T2}$

# The di-leptonic top basis vs Stops




With non-resonant production the overall di-top/di-stop mass can still be resolved…….better in some cases than others….


$\Delta\phi^{top}_{T2,W2}$
$\Delta\phi^{top}_{T1,W1}$
0.003
0.0025
0.002
0.001
0.0005
0
$\cos\theta^{top}_{W1}$
0.0025
0.002
0.0015
0.001
0.0005
0