

# Update on Top Squarks at 3TeV



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# Overview

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- Previous talk given at CLIC Workshop. Some of the same slides included.
- Motivations:
  - > Aim of study is to measure the top squark mass.
  - > Benchmark study for boosted top quarks at CLIC.
- SUSY model and top squark being studied.
- Overview of current analysis strategy.
- TMVA approach to event selection **NEW**
- Template fit to find top squark mass **NEW**

# Top squark details

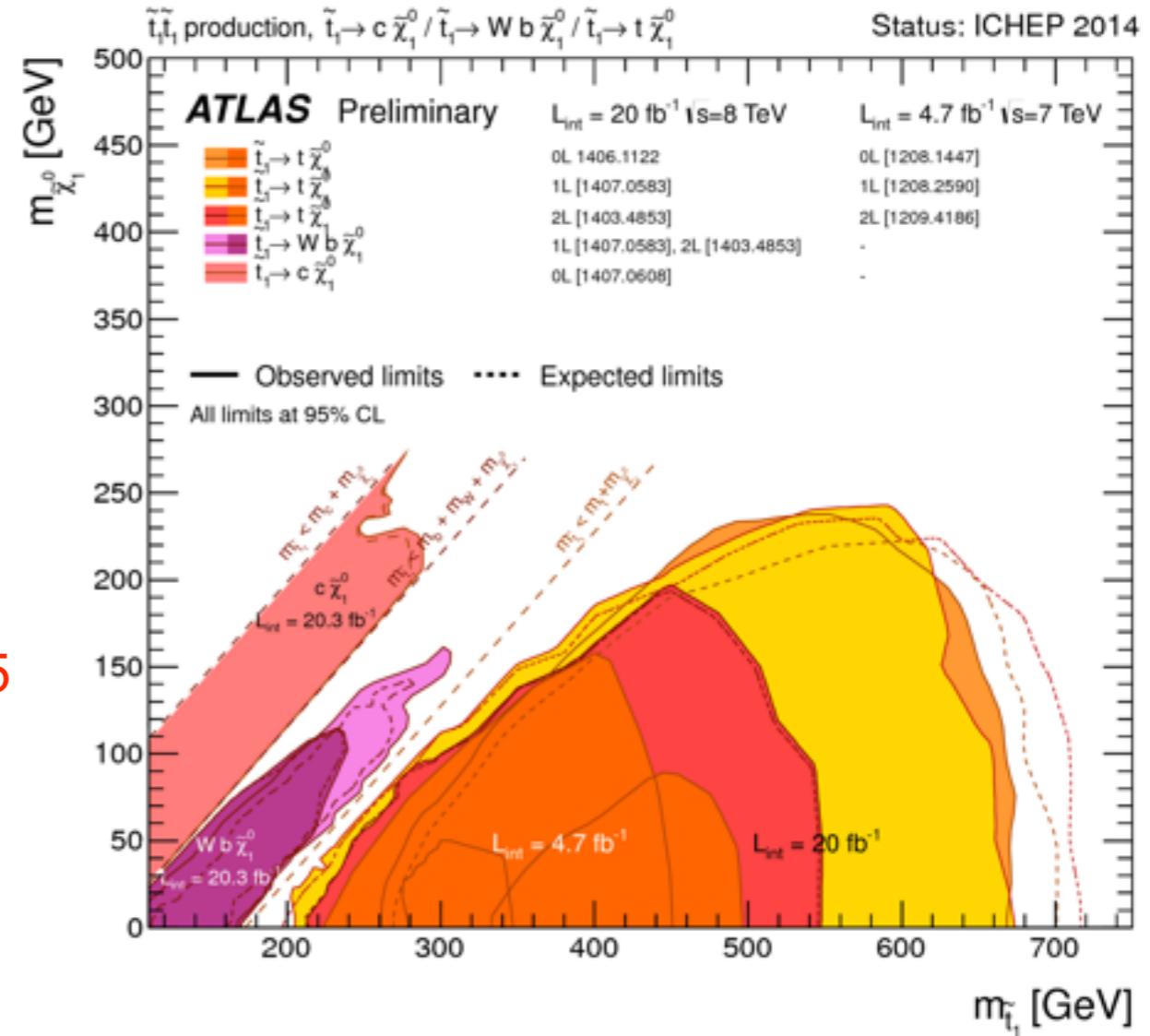
- Supersymmetry model selected is CLIC CDR Model 3.

- Mass of stop = 844 GeV. Stop being studied still compatible with LHC results.

- |   |                          |
|---|--------------------------|
| Process                                     | Cross section            |
| $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$ | 1.65 fb. • ProdID = 4195 |
| $e^+e^- \rightarrow t\bar{t}$               | 59 fb                    |

- Top squarks are pair produced in EW interactions so have to be at 3 TeV.

- Study assumes an integrated luminosity of  $2ab^{-1}$



# SUSY model details



- In the model the stop has several decay modes.

Main ones are:

$$BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0) = 52.4\%$$

$$BR(\tilde{t}_1 \rightarrow \chi_1^\pm b) = 34.1\%$$

$$BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0) = 13.2\%$$

- Decay modes of SUSY particles:

$$BR(\chi_1^\pm \rightarrow W\chi_1^0) = 99.7\%$$

$$BR(\tilde{\chi}_2^0 \rightarrow h^0\tilde{\chi}_1^0) = 94.6\%$$

- Masses in SUSY model:

$$M(\chi_1^\pm) = 487\text{GeV}$$

$$M(\tilde{\chi}_2^0) = 487\text{GeV}$$

$$M(\tilde{\chi}_1^0) = 357\text{GeV}$$

$$M(h^0) = 117.8\text{GeV}$$

# Top squark and top quark details



- Different decay modes of the stop leads to many final states.

$$\tilde{t}_1 \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \chi_1^\pm b \rightarrow W^+ W^- b \bar{b} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad (35.8\%)$$

- BR ( t  $\rightarrow$  Wb )  $\sim$  100%

$$\tilde{t}_1 \tilde{t}_1 \rightarrow t \bar{t} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+ W^- b \bar{b} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad (27.4\%)$$

- The channels are further characterised by the decays of the W boson.

$$\tilde{t}_1 \tilde{t}_1 \rightarrow t \bar{t} \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+ W^- b \bar{b} h^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad (13.7\%)$$

$$\tilde{t}_1 \tilde{t}_1 \rightarrow \chi_1^+ \chi_1^- b \bar{b} \rightarrow W^+ W^- b \bar{b} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad (11.6\%)$$

$$\tilde{t}_1 \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0 \chi_1^\pm b \rightarrow W^+ W^- b \bar{b} h^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad (9.0\%)$$

# Analysis Strategy

- Aim is to reconstruct stop mass as well as possible.
- To do this, reconstruct as many top quarks as possible. Channel currently being investigated is:



## ANALYSIS

FastJet



Force events into 6 jets using the kt algorithm, TightPFOs, R = 0.7.

LCFIPlus

Preselection Cuts

Multivariable Selection



Boosted Decision Tree

Template Fit

Mass Measurement

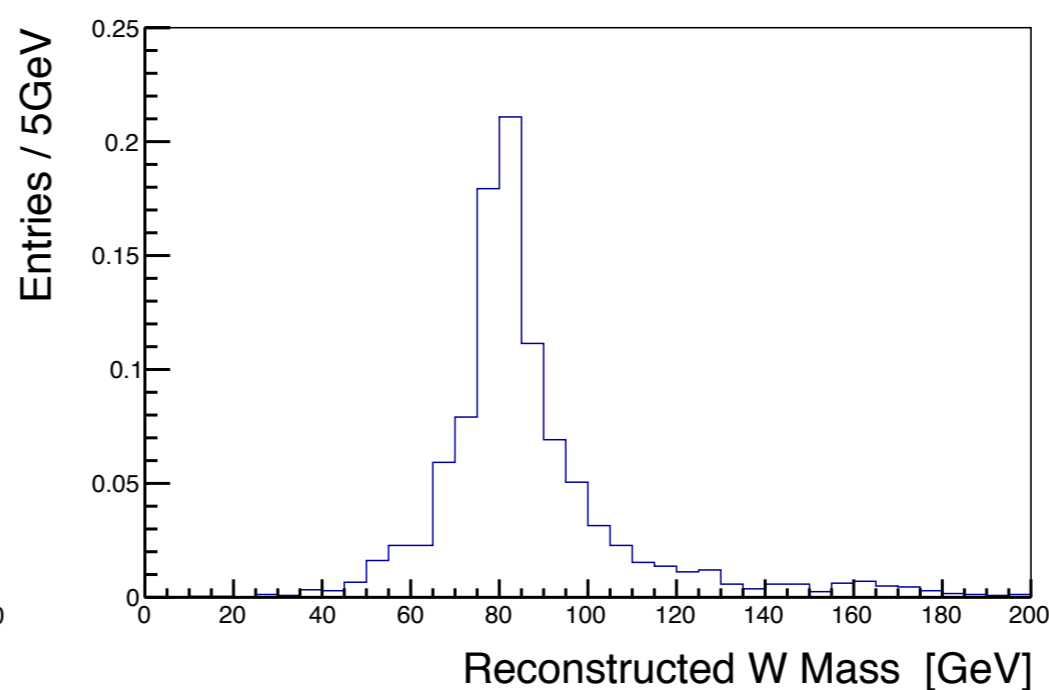
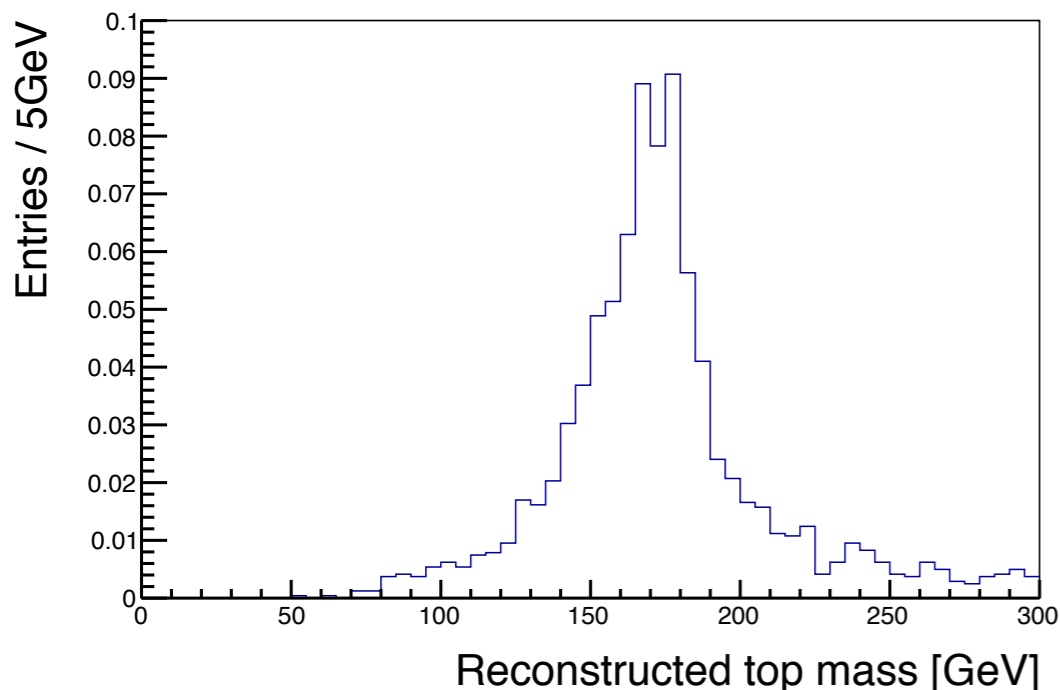
# W and top quark reconstruction

- Channel being investigated is:

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow WWb\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow qqqqb\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

- 6 jets in final state with the neutralinos escaping detector.
- Choose the jets which came from each W and top by minimising the quantity:

$$\chi^2 = \frac{(m_{j_1j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1j_2j_3} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_4j_5} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_4j_5j_6} - m_t)^2}{\sigma_t^2}$$



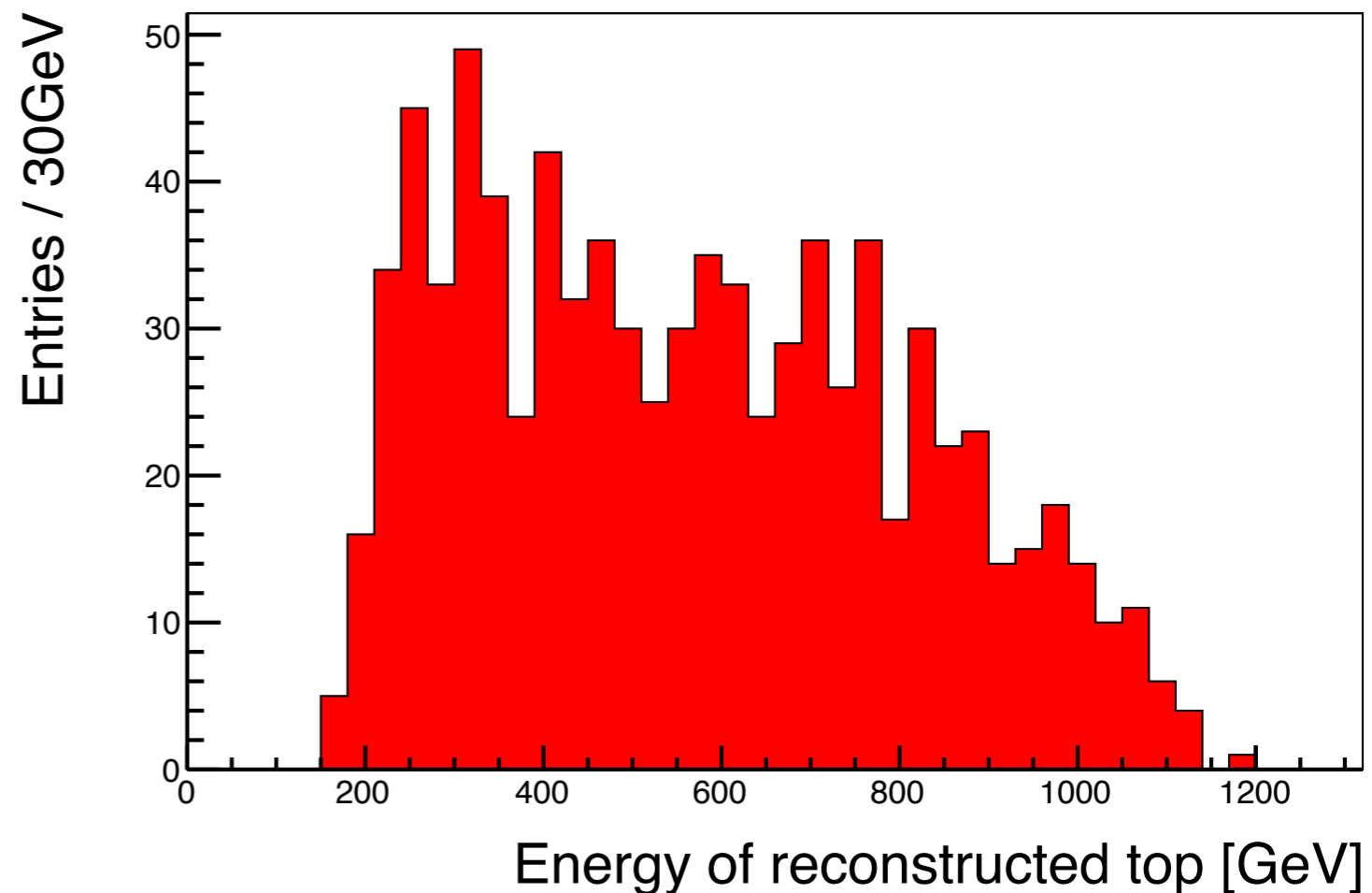
# Energy of reconstructed top

- The mass of the stop is sensitive to the energy spectrum of the top quarks that have decayed from a stop.

actual result is: 
$$m_{\tilde{t}_1} = \frac{\sqrt{s}}{2} \sqrt{1 - \frac{(E_{t_{max}} - E_{t_{min}})^2}{(E_{t_{max}} + E_{t_{min}})^2}}$$

- Signal events = 422

- Histogram scaled to  $2ab^{-1}$ .  
Corresponds to running CLIC at 3TeV for ~4 years.
- Beamstrahlung and ISR distort energy distribution. More statistics towards the minimum energy → Makes fitting the end points challenging.





# Background + Preselection cuts



- Backgrounds currently being considered are  $e^+e^- \rightarrow t\bar{t}$  and stop events other than

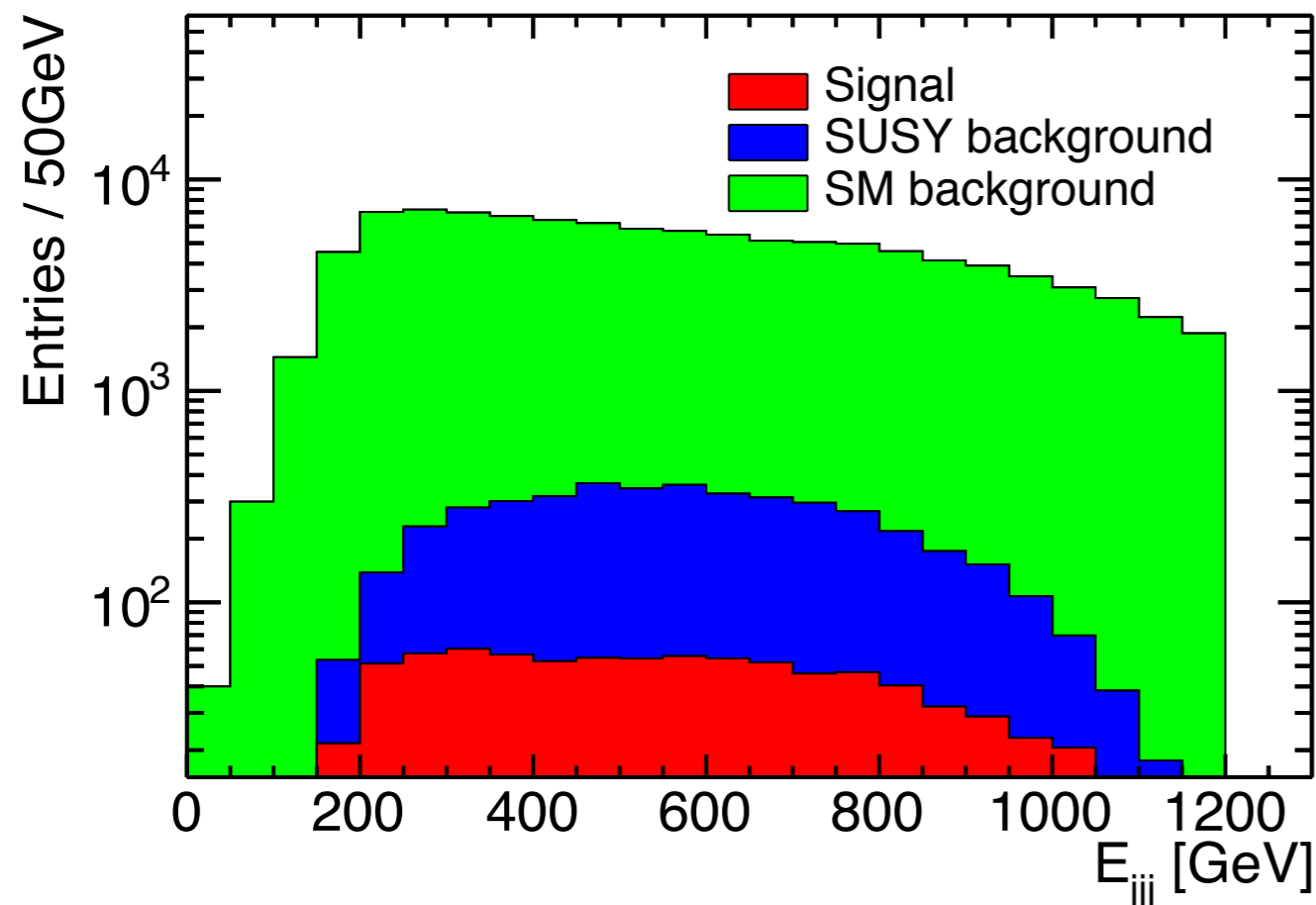
$$\tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow WWb\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow qqqb\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

- Current preselection cuts:
  - > No isolated leptons found using Isolated Lepton processor
  - > Visible energy in jets less than 2TeV
  - > Both  $E_{jjj} < 1.2\text{TeV}$ .

- 98% of signal events surviving and 26% of background events surviving.

- Energy spectrum of top quark with backgrounds:

- Histograms are stacked and normalised to 2ab.



# Event Selection

NEW

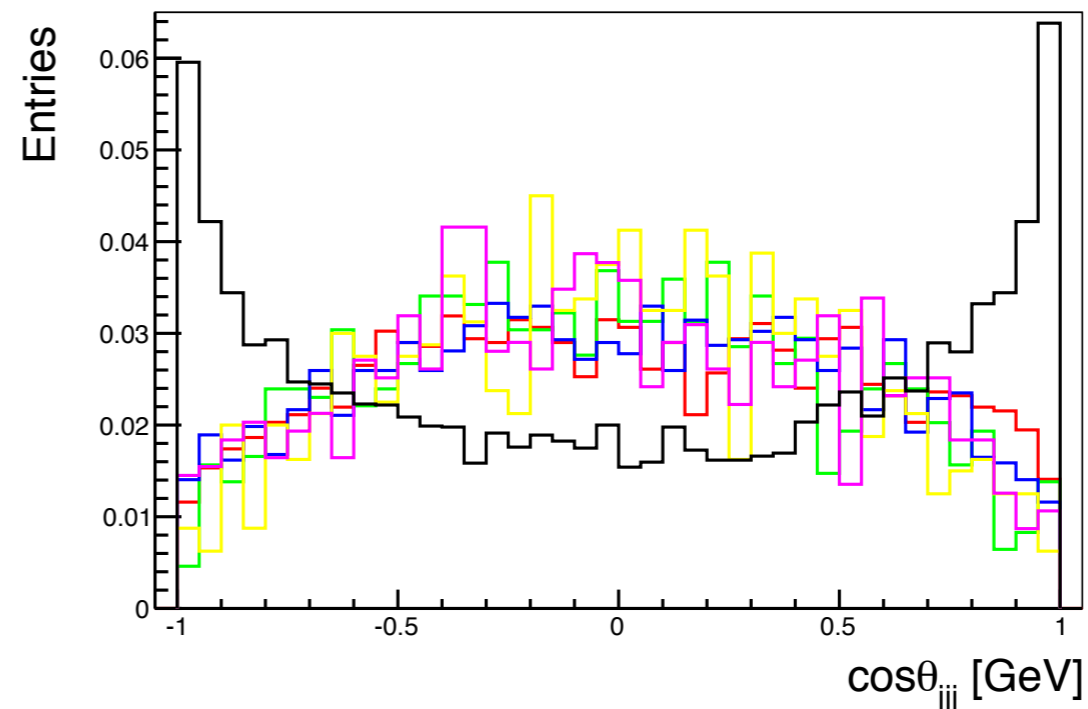
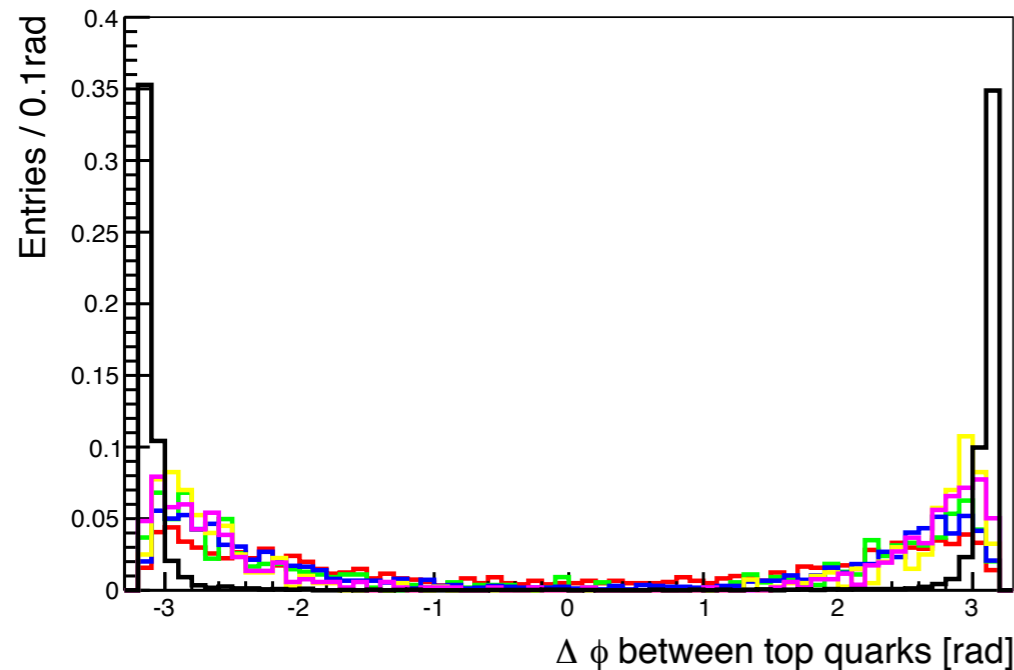


- Boosted Decision Tree in TMVA used for event selection. BDT trained with 10,000  $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$  and 30,000  $e^+e^- \rightarrow t\bar{t}$  events.

- 27 variables used in training of BDT. List of variables:

$E_{visible}$ ,  $P_T$ , Masses of top and W candidates,  $\theta^{miss}$ ,  $\cos\theta_{j_1j_2j_3}$ ,  $\cos\theta_{j_4j_5j_6}$ ,  $\Delta\phi$  between top candidates, Thrust, Oblateness, Acoplanarity, no. of tight pros in event,  $\Delta R$  between W candidates and b jets, jet transition values  $y_{34}, y_{45}, y_{56}, y_{67}, y_{78}$ , three highest b-tag and c-tag values

- 5 leading discriminating variables :  $P_T, \theta^{miss}, \cos\theta_{jjj}, \Delta\phi, E_{visible}$   
Two plotted below. Histograms normalised to unit area.



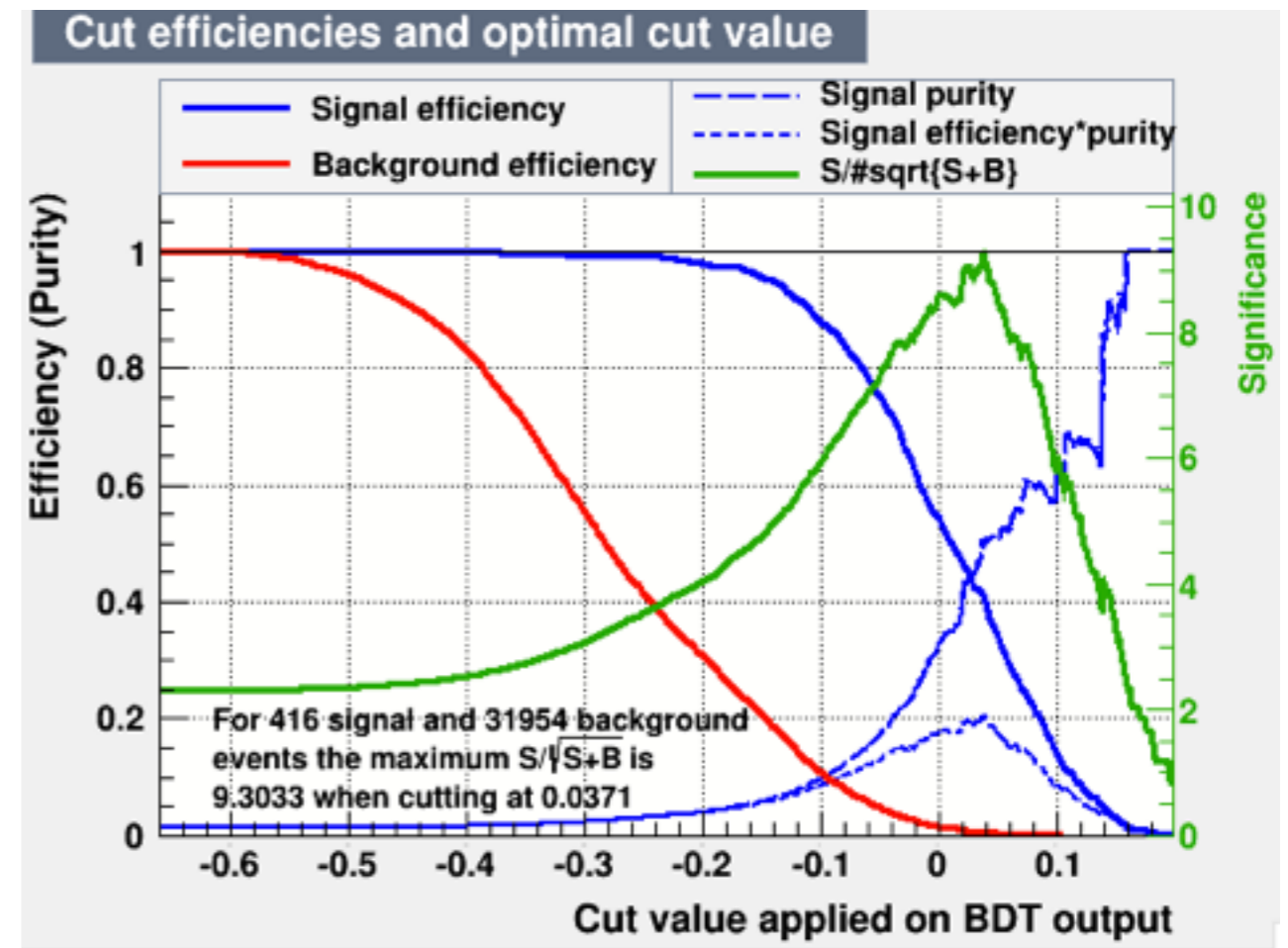
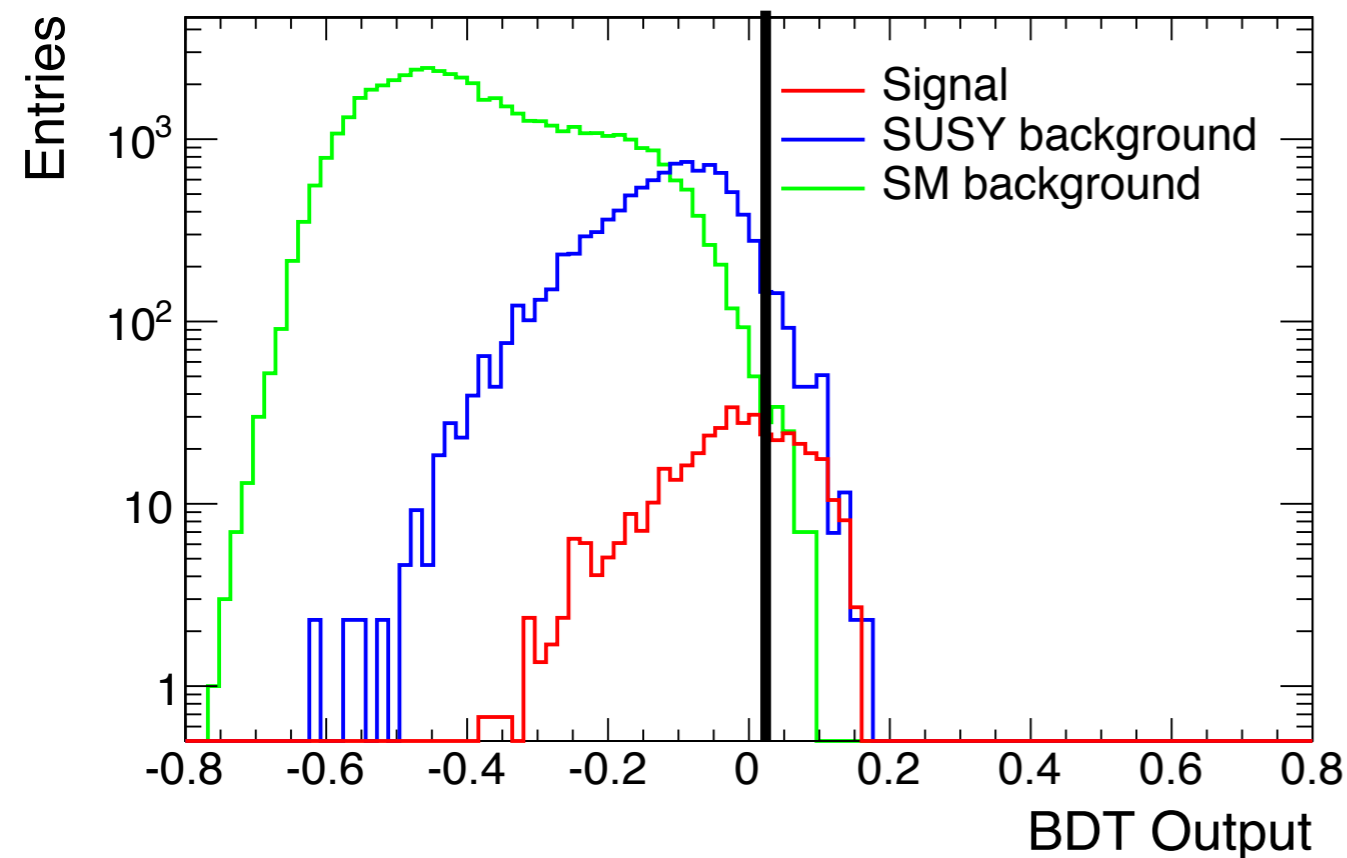
- Red = signal. Black =  $e^+e^- \rightarrow t\bar{t}$  (Hadronically). Other colours = SUSY Channels (Hadronically)

# BDT Performance

NEW



- Boosted Decision Tree used in adaptive boost mode.
- BDT cut selected to optimise the significance. Significance achieved was 9.3.
- 32% of signal events survive BDT cut. 2% other top squark events pass and 0.05% of tt background.

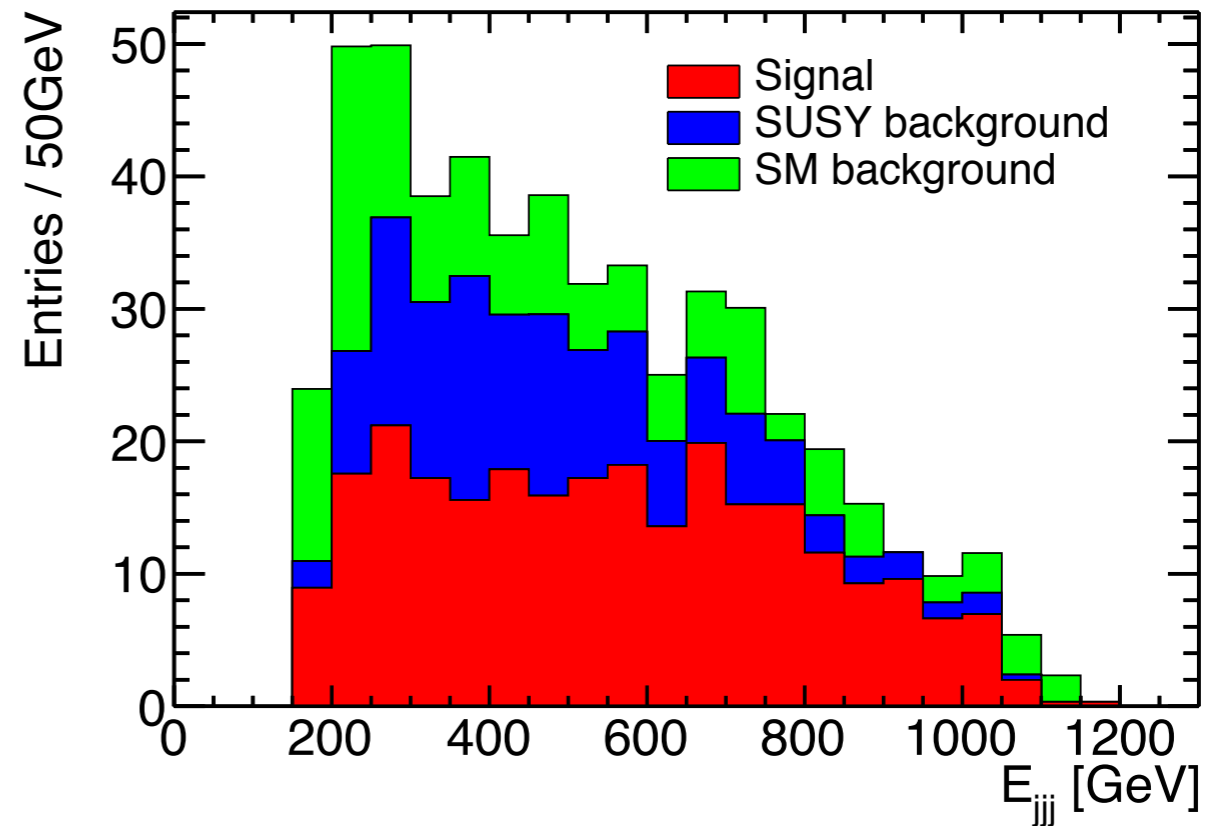
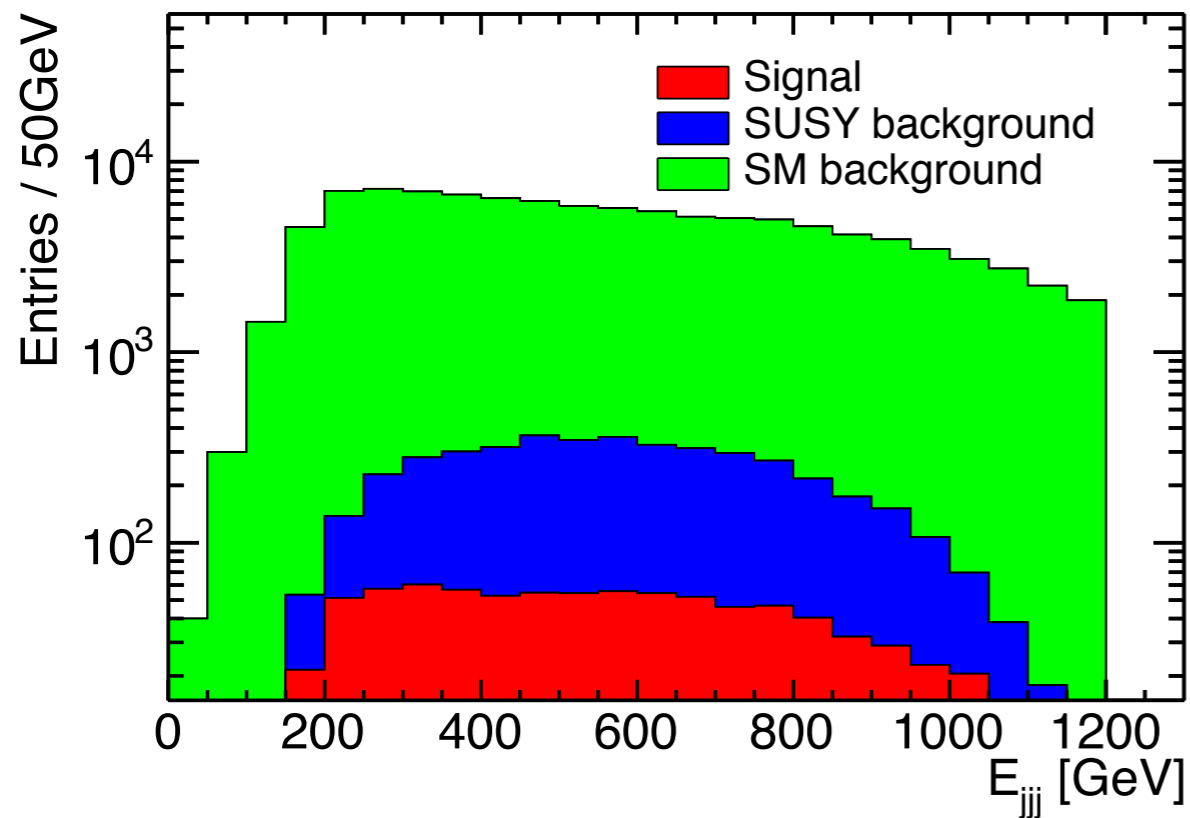


# Top quark energy spectrum

NEW



- Weights from BDT applied to data samples not used to train. Large SM background sample available so no scaling required.
- Top quark energy spectrum after preselection and after BDT cut is shown below. Significant improvement in the signal to background ratio.



# Template Fit

NEW



- Mass of stop1 =844GeV. cross section = 1.65fb.

- Templates currently available



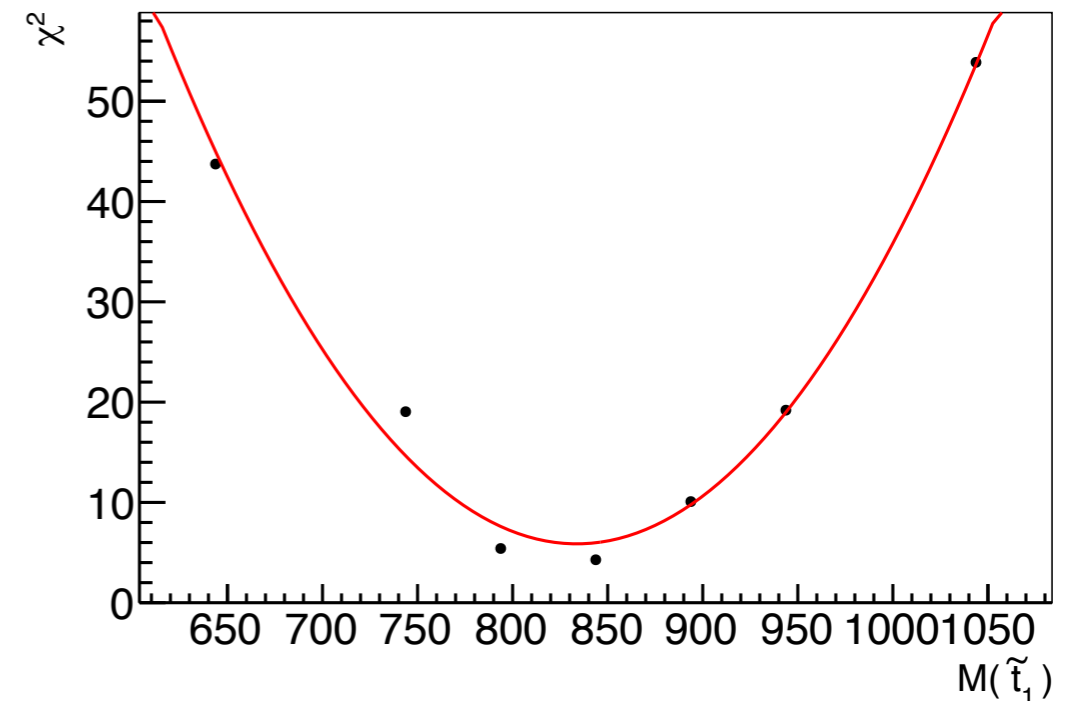
$M_{template}$	$\sigma$ (fb)	ProdID
$M(\tilde{t}_1) - 200\text{GeV}$	2.8	4368
$M(\tilde{t}_1) - 100\text{GeV}$	2.2	4321
$M(\tilde{t}_1) - 50\text{GeV}$	1.9	4370
$M(\tilde{t}_1)$	1.65	4195
$M(\tilde{t}_1) + 50\text{GeV}$	1.4	4319
$M(\tilde{t}_1) + 100\text{GeV}$	1.2	4335
$M(\tilde{t}_1) + 200\text{GeV}$	0.8	4333

- $\chi^2$  used in template fit:

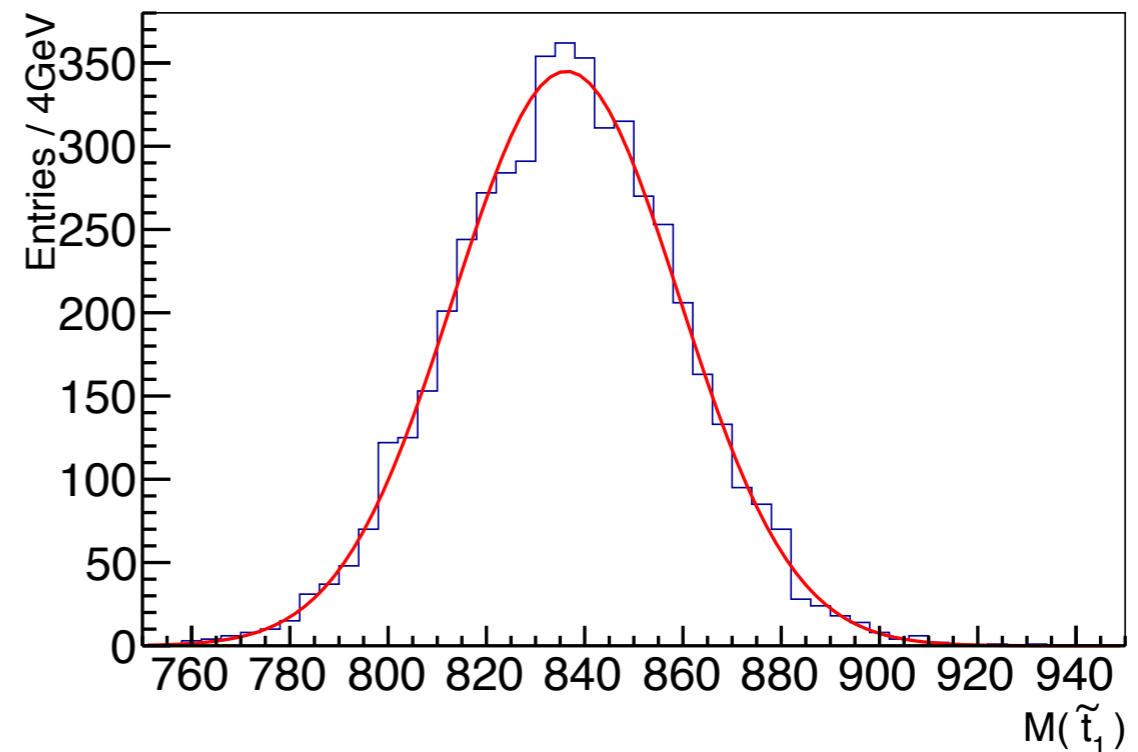
$$\chi^2 = \sum_i \frac{(n_{data_i} - n_{template_i})^2}{\sigma_{data_i}^2 + \sigma_{template_i}^2}$$

- Both the signal and SUSY background (other top squark decays) events are used from each top squark mass to create the templates.

- 2nd order polynomial fitted to  $\chi^2$  vs mass plot. Minimum of polynomial gives 834GeV. Toy MC used to find error on next slide.



- Toy MC method is used for statistical uncertainty. No. of entries in each bin is smeared with a gaussian of width  $\sqrt{n_{data_i}}$  .
- Mass measurement is repeated 5000 times. Gaussian fitted to mass distribution. Width of fitted gaussian is 23GeV.
- Mass of top squark measured as 834(23)GeV, agrees with the generator value of 844GeV.



- Current template fit assumes knowledge of cross section and

$$BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0) = 52.4\%$$

- Can implement template fit with the cross section as free parameter but not sure about  $BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0)$ . Should it also be left as a free parameter?
- Systematic Uncertainties. Intention is to consider systematic uncertainty due to event selection by using the templates to train the BDT.