

Search for Flavor Changing Neutral Currents in Top Quark Decays

$$t \rightarrow q\gamma$$

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The Standard Model

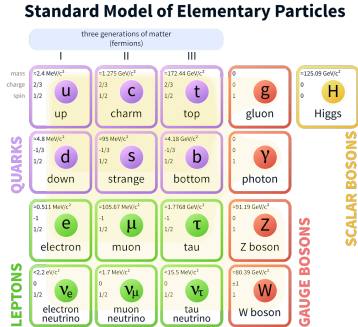


Figure: List of standard model particles

- Our current theory that attempts to explain everything
 - Experimentally precise and well behaved
 - Very few exceptions (i.e. Neutrino Mass, Matter-Antimatter Asymmetry, Dark Matter Abundance)

The Top Quark

- ▶ Heaviest fundamental particle, 172.5 GeV
- ▶ Lifetime $5 \times 10^{-25}\text{ s}$, decays before hadronization
 - ▶ Allows us to study the decay of a single quark

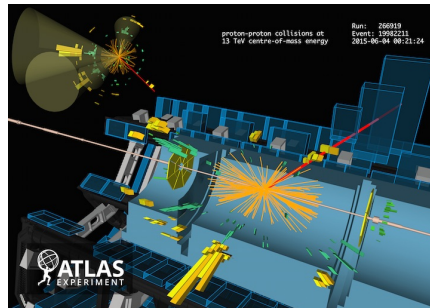


Figure: $t\bar{t}$ event in the ATLAS detector

Top Quark Pair Production

- ▶ Leading order processes for top quark production
 - ▶ Quark-antiquark annihilation $\approx 10\%$
 - ▶ Gluon-gluon fusion $\approx 90\%$

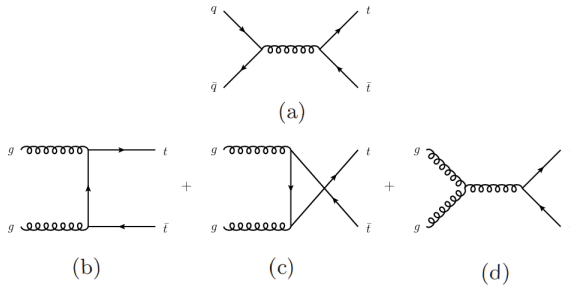


Figure: Leading order $t\bar{t}$ diagrams

Top Quark Pair Production

- At $\sqrt{s} = 13\text{TeV}$ for $m_t = 172.5\text{GeV}$, $\sigma_{t\bar{t}} = 831.76\text{pb}$

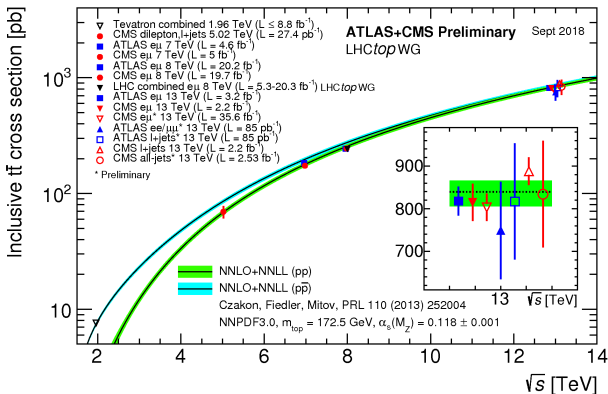


Figure: $t\bar{t}$ production cross section [TopWGSummaryPlots]

Top Quark Decays

- Standard model top branching ratio to $bW \simeq 100\%$

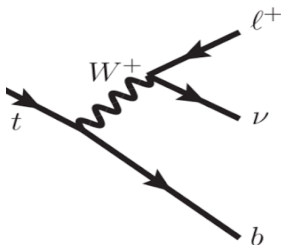


Figure: Leptonic final state diagram for a top decay

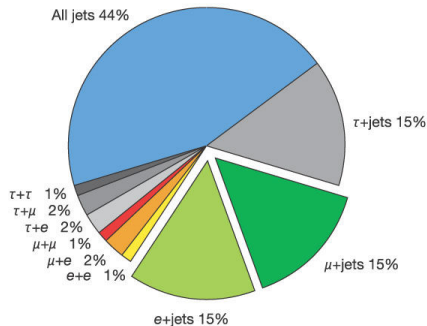
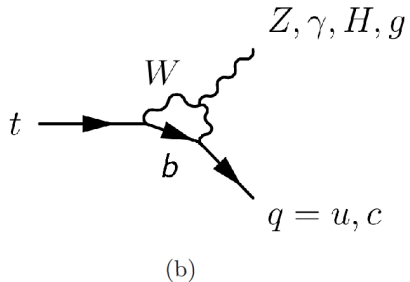
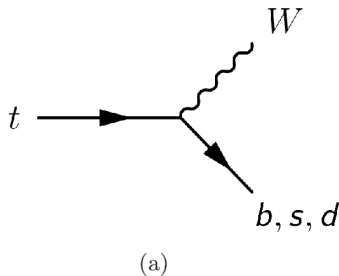


Figure: Top quark pair decay final states [Nature]

Top Quark Decays in the SM

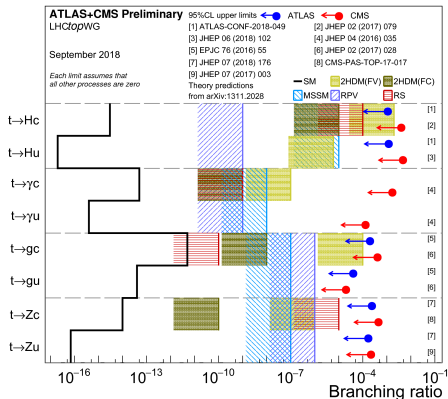


- ▶ $t \rightarrow bW \approx 99.83\%$
- ▶ $t \rightarrow sW \approx 0.16\%$
- ▶ $t \rightarrow dW \approx 0.01\%$

- ▶ $t \rightarrow q_{u,c}X \approx 10^{-17} - 10^{-12}$

Top Flavor Changing Neutral Currents

► Current Limits on FCNC Decays



► Limits on $t \rightarrow \gamma q$ processes: arXiv:1908.08461

- $t \rightarrow \gamma u < 6.1 \times 10^{-5}$
- $t \rightarrow \gamma c < 2.2 \times 10^{-4}$

Monte Carlo Production of FCNC Signal Samples

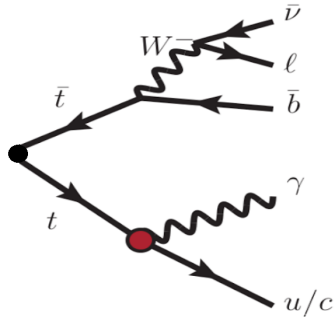
- ▶ Due to the low cross sections we must create our own Monte Carlo Samples for our Signal
- ▶ An effective field theory approach was taken in the creation of the model
- ▶ This model takes advantage of dimension-6 operators

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \mathcal{L}^{eff} \text{ where } \mathcal{L}^{eff} = \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)}$$

$$\mathcal{L}_{tq\gamma}^{eff} = C \sigma^{\mu\nu} q_\nu (\lambda_{ct}^L P_L + \lambda_{ct}^R P_R) t A_\mu + H.c.$$

FCNC: What are we looking for? $t\bar{t} \rightarrow W(\rightarrow l\nu)b + q\gamma$

- ▶ Final state topology
 - ▶ One Neutrino, from W
 - ▶ One Lepton, from W
 - ▶ One B-jet, SM top
 - ▶ One Photon, FCNC Top
 - ▶ One Jet, FCNC Top

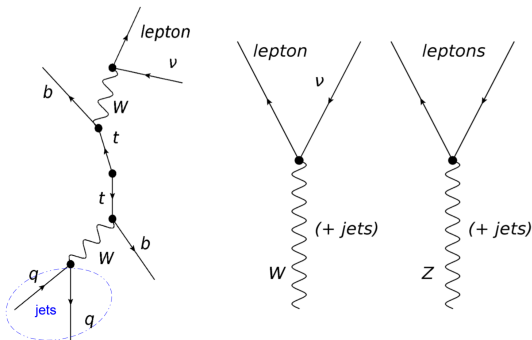


Object Preselection

- ▶ We preselect events with objects that look like our expected topology
- ▶ Require:
 - ▶ Exactly one lepton (e or μ) ≥ 25 GeV
 - ▶ Exactly one Good photon ≥ 25 GeV
 - ▶ Missing Transverse Energy ≥ 30 GeV
 - ▶ ≥ 2 Jets (at least one being b-tagged)

Background Processes

- Due to all of the processes at hadron colliders it is important to model similar event topologies well
- Major backgrounds include $t\bar{t}$, W +Jets, Z +Jets, + processes with an associated photon

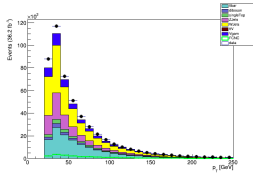


Preselection Objects

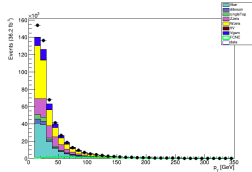
Signal MC Scaled to 1% $\sigma_{t\bar{t}}$, No Overlap Removal but no dedicated gamma samples

Electron Channel

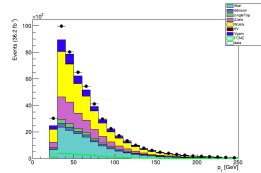
► Leading Jet p_T



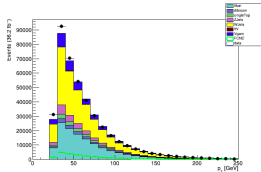
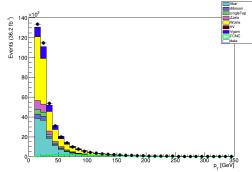
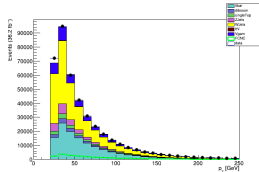
► Lead Photon



► Lepton E



Muon Channel



No Overlap Removal but no dedicated gamma samples - Overall Scale Factors Needed

Neural Network Architecture

- ▶ Using Keras on top of Tensorflow various input parameters are tested for model behavior
- ▶ A Dense Neural Network with variable number of input variables and hidden layers are explored
- ▶ Cut optimization has been performed with full Run 2 luminosity for potential reach of the search

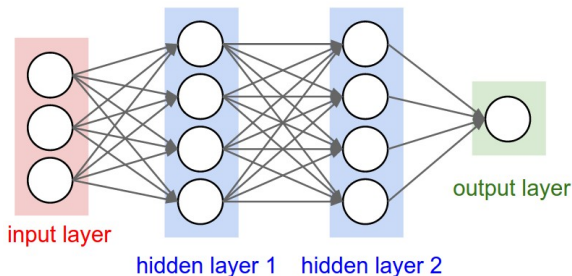


Figure: [Ref: Neural Network]

Neural Network Model Inputs

- ▶ Using keras on top of tensorflow various input parameters are tested for model behavior
- ▶ Networks are set up with 1 input layer, 2 hidden layers with 10 nodes (+1 bias node) [Ref: Bias], and 1 output node
- ▶ Each hidden layer has 20% dropout to prevent overtraining by removing codependency between nodes
- ▶ Batch size of 100 used and each network is allowed 200 epochs (with patience=50), all models converge and end early with reasonable batch sizes
- ▶ Optimizer: Adam
- ▶ Loss Function: Binary Cross Entropy

Cut Optimization

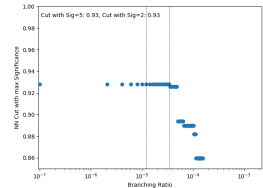
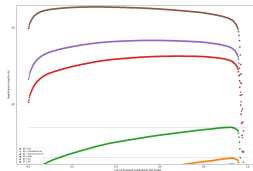
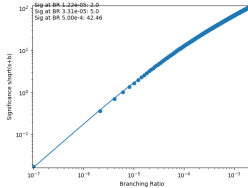
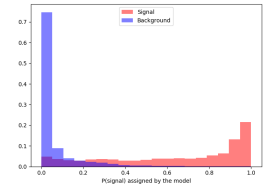
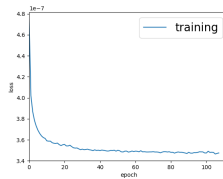
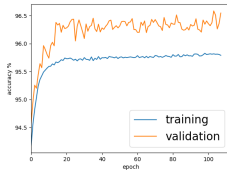
- Reweighting the number of events the model saw by taking advantage of the loss function helps signal/background discrimination

$$\text{Loss} = -\frac{1}{N} \sum_{i=1}^N y_i \log(p(y_i)) + (1 - y_i) \log(1 - p(y_i))$$

- y - binary indicator (0 or 1) if class label is the correct classification for observation
- p - predicted probability observation is the class label (0 or 1)

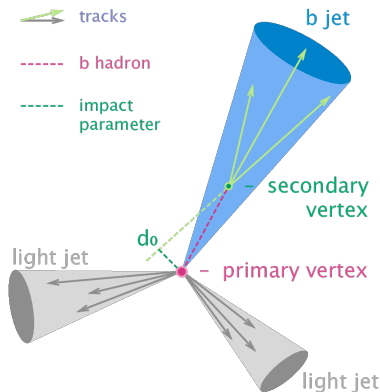
Neural Network Example

μ +jets Channel Example



B-tagging

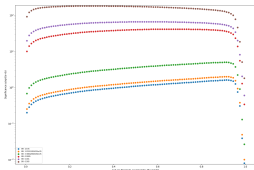
- ▶ B Hadrons travel a measureable distance before decay
- ▶ Tracks originate from outside of interaction point (Secondary Vertex)
- ▶ Backtracking tracks in displaced vertex gives an impact parameter
- ▶ Decay chain MVA attempts to reconstruct decay of the jet
- ▶ Outputs of these algorithms used in a BDT to determine if a Jet is from a b-quark



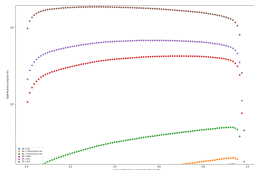
Neural Network B-Tagging Results

Electron Channel

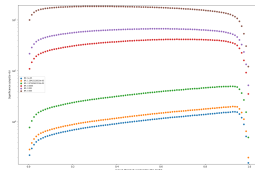
► 70% Working Point



► 77% Working Point

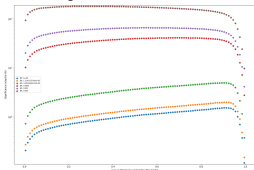


► 85% Working Point

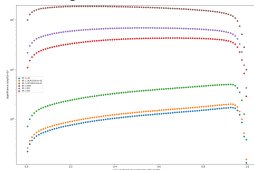


Muon Channel

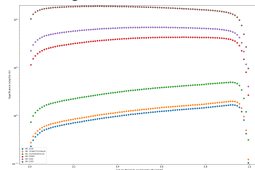
BR with Sig=2: 1.25×10^{-5}



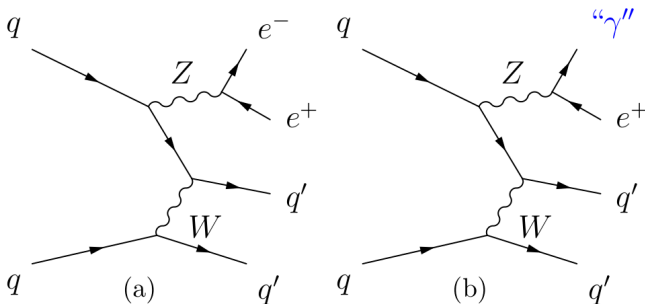
BR with Sig=2: 1.23×10^{-5}



BR with Sig=2: 1.28×10^{-5}



Fake Rate Studies

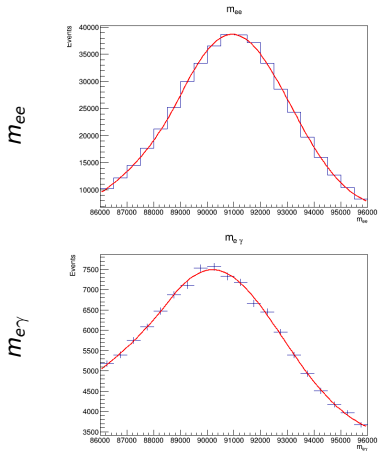


Want to be able to correct the number of fake photons predicted in MC to those present in Data

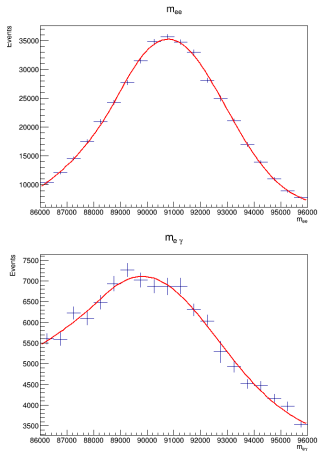
$m_{ee}, m_{e\gamma}$

Data and MC

► Data



► Monte Carlo



Scale Factor

$$FR^{e\text{-fake}} = \frac{N_{e,\gamma}}{N_{e,e} + N_{e,\gamma}}$$

$$SF_{FR}^{e\text{-fake}} = \frac{FR_{\text{data}}^{e\text{-fake}}}{FR_{\text{MC}}^{e\text{-fake}}}$$

Basic Scale Factor can be calculated for the entire spectrum:

$$FR_{\text{data}}^{e\text{-fake}} = 0.201$$

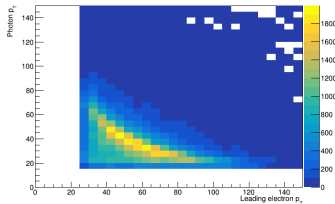
$$FR_{\text{MC}}^{e\text{-fake}} = 0.212$$

$$SF_{FR}^{e\text{-fake}} = 0.953$$

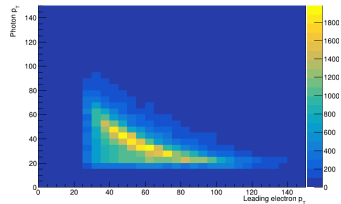
Data and MC Distributions

► Data

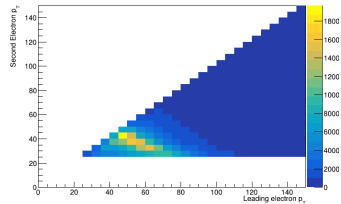
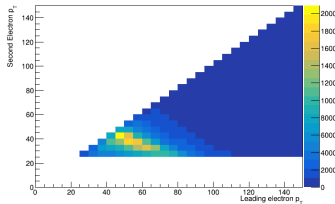
$e\gamma$ region



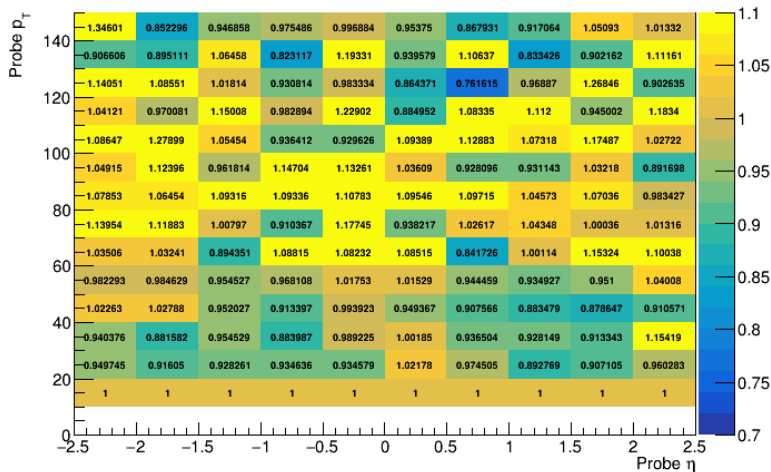
► Monte Carlo



ee region



2D Fake Rate



Fake rate will be recalculated using the newest ntuples soon

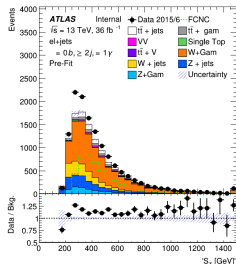
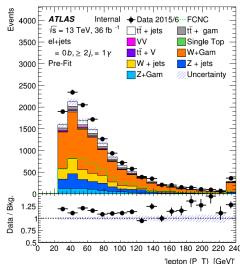
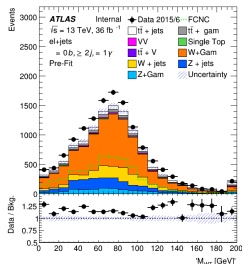
Analysis Plots

	VR1: $W + \gamma$	VR2: $t\bar{t} + \gamma$	VR3: $t\bar{t}/W + \text{Jets}$	CR1: $W + \text{Jets Rich}$	CR2: $t\bar{t}$ Rich	SR
n_γ	=1	=1	=0	= 0	=0	=1
n_{jet}	≥ 2	≥ 4	=4	=3	≥ 5	≥ 2
$n_{b_{\text{jet}}}$	=0	=1	=1	=1	=1	=1
n_{lepton}	=1	=1	=1	=1	=1	=1
Neural Network Cut	-	< NNCut	-	-	-	> NNCut

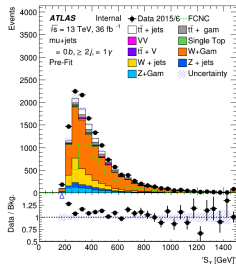
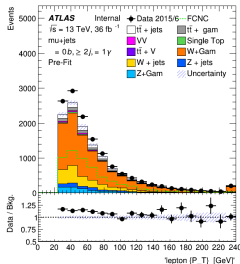
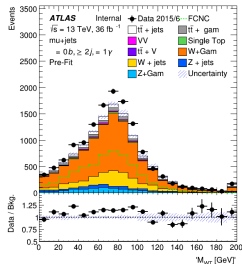
Additional cuts are employed as well to slim out certain backgrounds.
 The following plots are for MC16a and Data 2015/2016, signal is scaled to 1% $\sigma_{t\bar{t}}$ except for SR where it is scaled to 0.01% $\sigma_{t\bar{t}}$

VR1: $W + \gamma$ VR Plots - m_T^W , lepton p_T , S_T

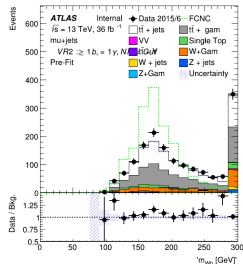
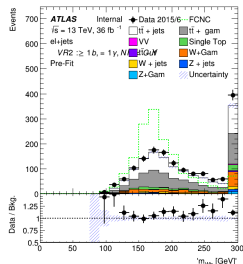
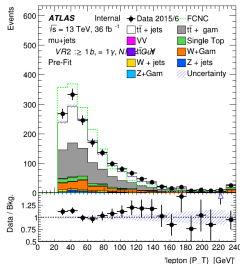
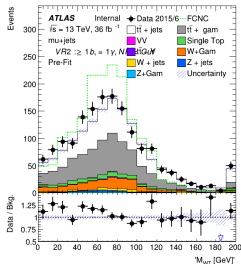
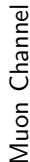
Electron Channel



Muon Channel



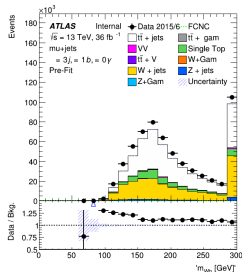
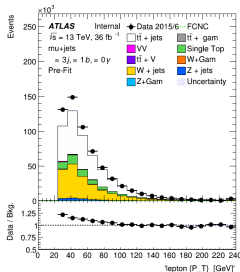
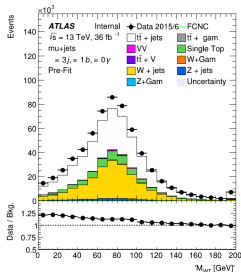
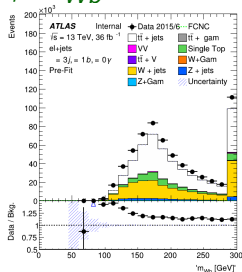
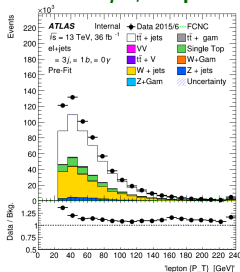
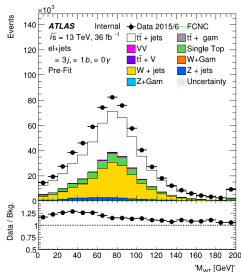
Electron Channel



W+Jets Rich CR1 Plots - m_T^W , lepton p_T , m_{Wb}

Electron Channel

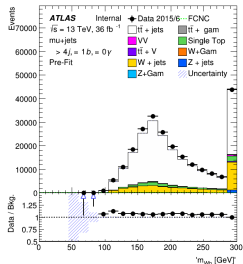
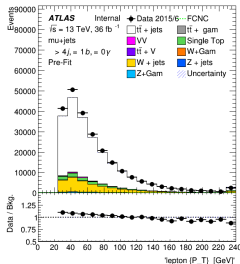
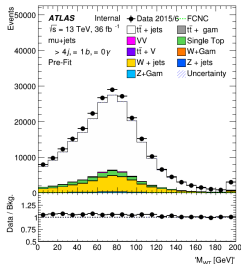
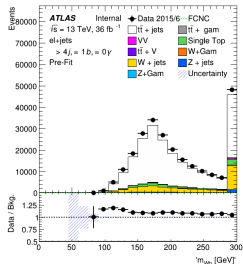
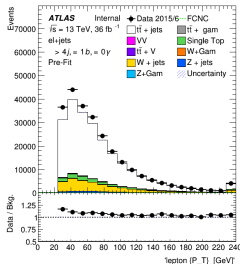
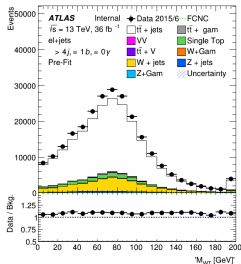
Muon Channel



$t\bar{t}$ Rich CR2 Plots - m_{T}^W , lepton p_T , m_{Wb}

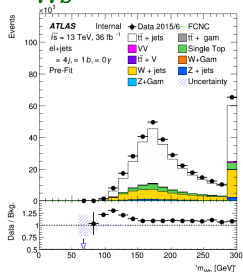
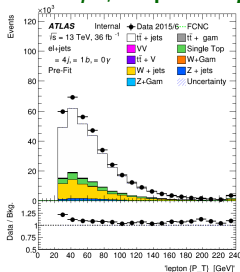
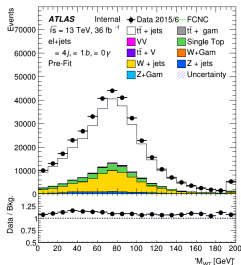
Electron Channel

Muon Channel

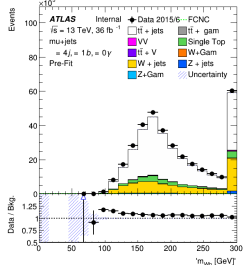
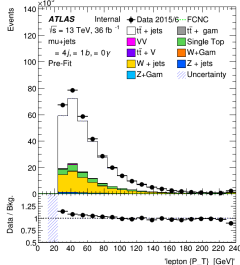
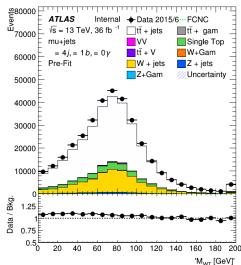


$t\bar{t}/W + \text{Jets}$ VR3 Plots - m_T^W , lepton p_T , m_{Wb}

Electron Channel

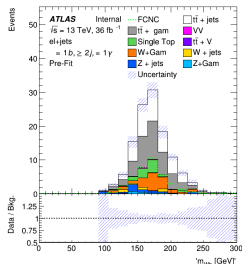
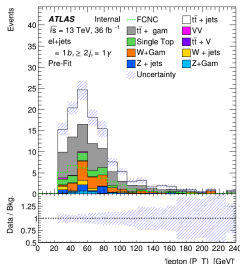
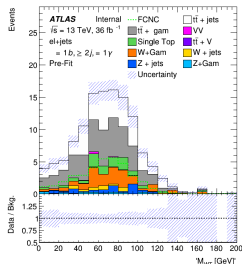


Muon Channel

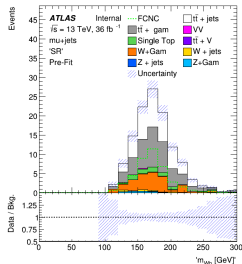
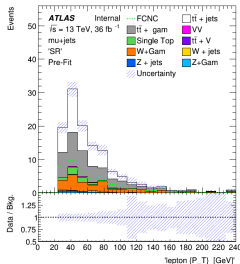
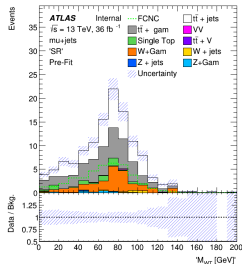


SR Plots - m_T^W , lepton p_T , m_{Wb}

Electron Channel

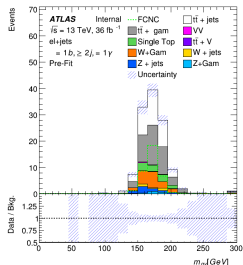
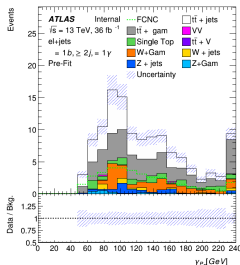
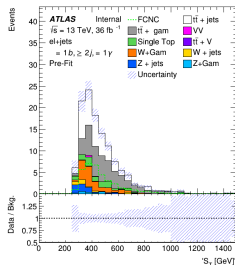


Muon Channel

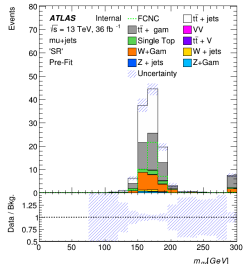
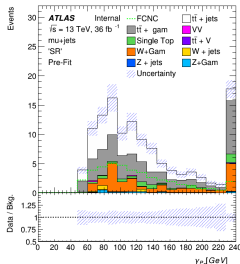
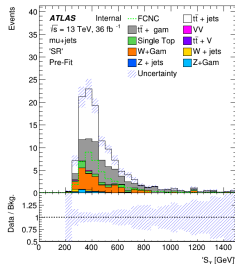


SR Plots - S_T , γ p_T , $m_{a\gamma}$

Electron Channel



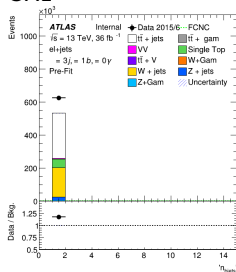
Muon Channel



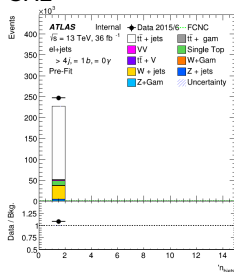
Scale Factor Calculation based on CR1/CR2

Further scale factors will be applied to the samples to account for mismodeling of the MC. SF calculated based on the control regions (CR1,2) and test its performance in the validation region (VR3)

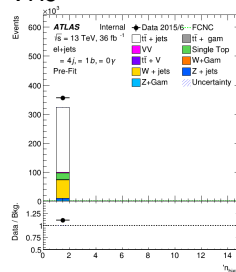
CR1



CR2



VR3



$$\begin{bmatrix} N(W)_{CR1} & N(t\bar{t})_{CR1} \\ N(W)_{CR2} & N(t\bar{t})_{CR2} \end{bmatrix} \begin{bmatrix} W_{SF} \\ t\bar{t}_{SF} \end{bmatrix} = \begin{bmatrix} N(\text{data} - \text{bkg})_{CR1} \\ N(\text{data} - \text{bkg})_{CR2} \end{bmatrix}$$

To-Do

- ▶ Checking all MC/Data not just MC16a/2015/16
- ▶ Calculation and verification of Scale Factor for $t\bar{t}$ and W+Jets
- ▶ Recalculation of $e \rightarrow \gamma$ Fake Rate SF using updated samples
- ▶ Calculation of $j \rightarrow \gamma$ Fake Rate SF using Data Driven ABCD method
- ▶ Systematics Grid Run on Signal Region to get systematic variations
 - ▶ Learning how to apply systematics to TRExFitter
- ▶ Learning how to do CL_s method for limit setting in TRExFitter Framework

Timeline

- ▶ Dissertation Chapters 1-4 Complete (4 not copyedited yet)
 - ▶ Chapter 1 - Very Brief Introduction
 - ▶ Chapter 2 - Theoretical Background
 - ▶ Chapter 3 - The LHC and ATLAS
 - ▶ Chapter 4 - Event Simulation and Object Reconstruction
- ▶ Aiming to continue writing about 1 chapter per month, although it gets a little iffy with the Analysis Chapter
 - ▶ Remaining Chapters
 - ▶ Chapter 5: Search Strategy - Background Discussion, NN Discussion
 - ▶ Chapter 6: Analysis and Results
 - ▶ Chapter 7: Outlook for Future Searches
 - ▶ Various appendices
- ▶ Applying to Medical Physics Fellowships over the next 2 months
 - ▶ All appointments start July 1
- ▶ Finishing analysis to-do list by mid-late Jan.
- ▶ Would like to plan defense in mid-late Feb.

Backup

Neural Network Model Inputs

$$\text{Separation} = \sum_i^{\text{bins}} \frac{n_{si} - n_{bi}}{n_{si} + n_{bi}}$$

mu+jets channel

Variable	Separation
photon0iso	41.18
mqgam	28.27
photon0pt	24.07
mtSM	11.60
mlgam	7.56
deltaRjgam	5.64
deltaRbl	4.42
MWT	3.34
ST	3.30
nuchi2	3.12
jet0pt	2.81
njets	2.07
smchi2	1.89
wchi2	1.87
jet0e	1.52
deltaRlgam	1.17
leptone	0.87
deltaRjb	0.86
met	0.68
bjet0pt	0.52
leptoniso	0.27

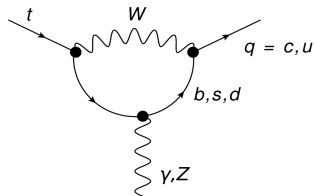
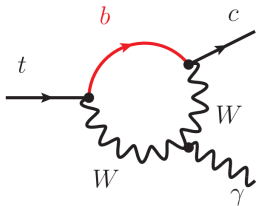
e+jets channel

Variable	Separation
photon0pt	23.14
mqgam	22.73
photon0iso	18.70
mtSM	11.02
mlgam	9.53
deltaRbl	5.00
deltaRjgam	4.60
ST	3.83
MWT	3.16
jet0pt	2.47
njets	1.70
nuchi2	1.59
deltaRlgam	1.40
wchi2	1.33
smchi2	1.09
deltaRjb	0.88
leptone	0.85
leptoniso	0.56
bjet0pt	0.50
met	0.47

Input Variables

```
['photon0iso', 'photon0pt', 'mqgam', 'mlgam', 'mtSM', 'deltaRjgam', 'deltaRbl',  
'MWT', 'ST', 'njets', 'wchi2', 'jet0pt', 'deltaRlgam', 'leptone', 'met', 'bjet0pt']
```

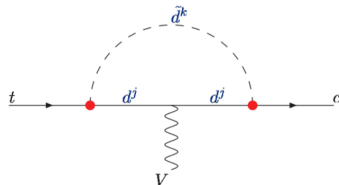
FCNC Diagrams



A Couple of BSM Diagrams

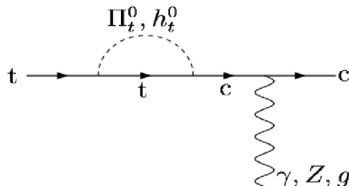
- R-parity-violating supersymmetric models

[arXiv:hep-ph/9705341]



- Top-color-assisted technicolor models

[arXiv:hep-ph/0303122]



Jets/AntiKT

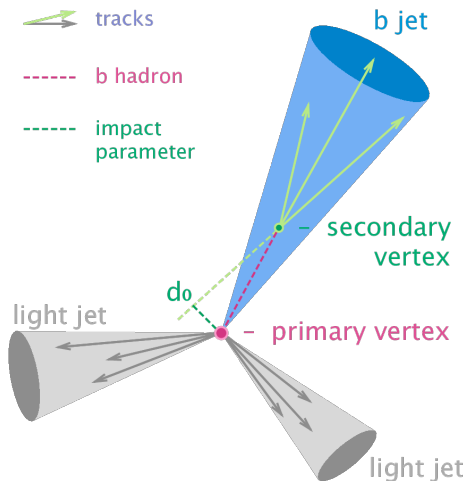
$$d_{ij} = \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{p_{ti}^2}$$

$$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

- ▶ Find minimum of entire set of $\{d_{ij}, d_{iB}\}$
- ▶ If d_{ij} is the minimum particles i, j are combined into one particle and removed from the list of particles
- ▶ If d_{iB} is the minimum i is labelled as a final jet and removed from the list of particles
- ▶ Repeat until all particles are part of a jet with distance between jet axes Δ_{ij} is greater than R

B-tagging



$$\mathcal{L}_{tq\gamma}^{\text{eff}} = -e\bar{c}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(\lambda_{ct}^L P_L + \lambda_{ct}^R P_R)tA_\mu + H.c.$$