Search for the Flavor Changing Neutral Current, $t \rightarrow q\gamma$ in Top Pair Events Using the ATLAS Detector

Jason Barkeloo

April 16, 2020

UNIVERSITY OF OREGON

Welcome!

Thank you for your flexibility given our current situation!

Defense proceedings:

- Open/public presentation in this room with followup questions
- Committee and myself will adjourn to a separate room to conclude
- Committee will deliberate and I will return to this room

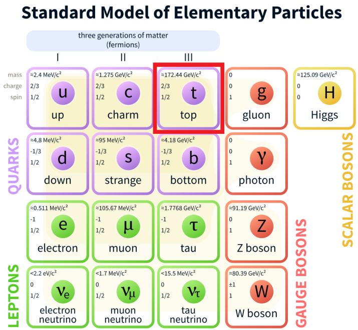
General Guidelines:

- Please mute if not speaking

Thank you for attending!

Overview

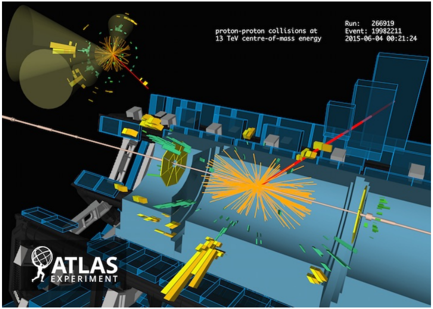
The Standard Model



- Best working description of fundamental particles and their interactions
  - Experimentally precise and well behaved

The Top Quark

- Heaviest fundamental particle, $172.5 GeV$
- Lifetime $5x10^{-25}s$, decays before hadronization
  - Allows us to study the decay of a single quark



Top Quark Pair Production

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

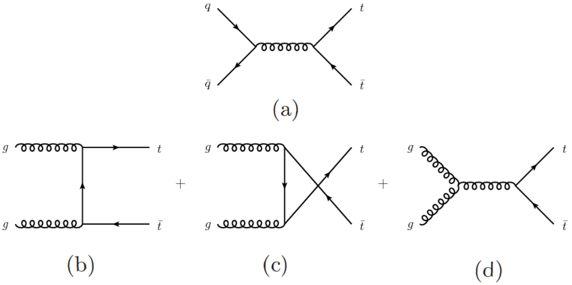


Figure: Leading order $t\bar{t}$ diagrams

Top Quark Pair Production

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

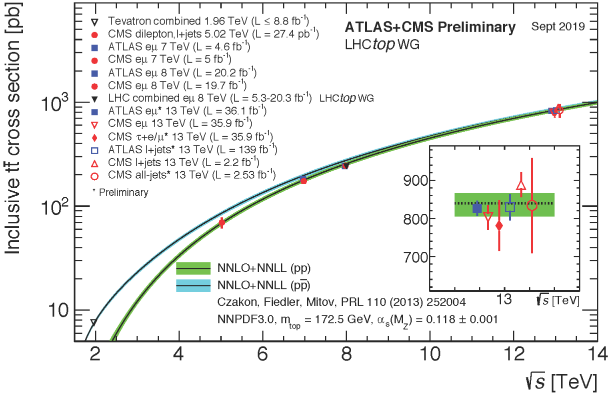


Figure: $t\bar{t}$ production cross section [TopWGSummaryPlots]

Top Quark Decays

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

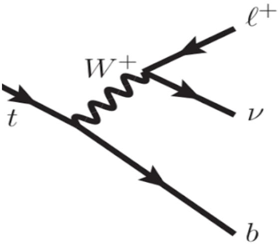


Figure: Leptonic final state diagram for a top decay

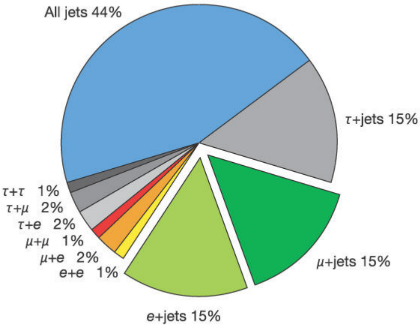
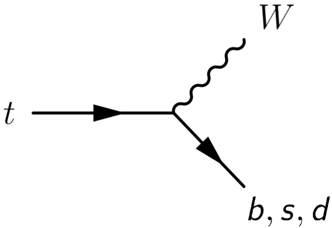
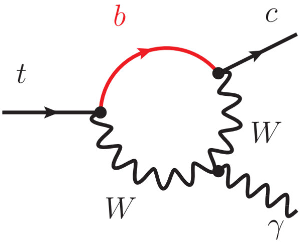


Figure: Top quark pair decay final states [Nature]

Top Quark Decays in the SM





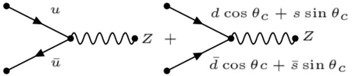
- $t \rightarrow bW \approx 99.83\%$
- $t \rightarrow sW \approx 0.16\%$
- $t \rightarrow dW \approx 0.01\%$

- $t \rightarrow q_{u,c}X \approx 10^{-17} - 10^{-12}$
- Limits on $t \rightarrow \gamma q$ processes: [Phys.Lett. B800 135082]
  - $t \rightarrow \gamma u < 2.8x10^{-5}$
  - $t \rightarrow \gamma c < 18x10^{-5}$

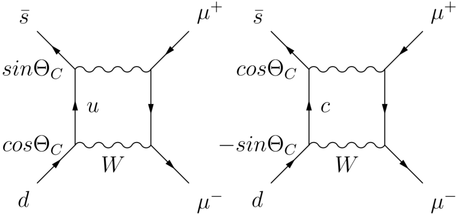
GIM Mechanism

- Cabibbo model - 3 quarks (u, d, s)
- Studies of kaon decays showed the existence of $K^+ \rightarrow \mu^+ \nu_\mu$ but an absence of predicted $K_L^0 \rightarrow \mu^+ \mu^-$
- Even in the absence of a tree level decay K_L^0 decay the box diagram would be possible through an exchange of W bosons
- Weak neutral current interactions in the uds model have the form

$$u\bar{u} + (d\bar{d}\cos^2\theta_C + s\bar{s}\sin^2\theta_C)) + (s\bar{d} + d\bar{s})sin\theta_C cos\theta_C$$



GIM Mechanism



- Glashow, Iliopoulos, and Maiani [Phys. Rev. D (1970)] propose a machanism through which FCNCs are suppressed in loop diagrams
  - Introduction of charm quark
- Kaon decays imply no neutral current/natural suppression of neutral current

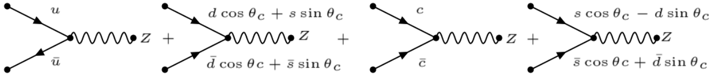
GIM Mechanism

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$

- The addition of the charm changes our weak neutral current interactions
- With four quarks the weak neutral interactions now have the form:

$$u\bar{u}+c\bar{c}+(d\bar{d}+s\bar{s})\cos^2\theta_C+(s\bar{s}+d\bar{d})\sin^2\theta_C+(s\bar{d}+d\bar{s}-d\bar{s}-s\bar{d})sin\theta_C cos\theta_C$$

- Flavor changing neutral current diagrams cancel out at tree level (as $m_c \to m_u$)



CKM Matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}$$

Figure: CKM Matrix

- Decay rates proportional to $|V_{tX}|^2$
- Top decay through a $W^{\pm}$ boson is a charged current interaction.
- Flavor changing processes are proportional to off-diagonal elements of the CKM matrix
- GIM/CKM suppression of these FCNC processes in the Standard Model make them unlikely to be seen without some new physics

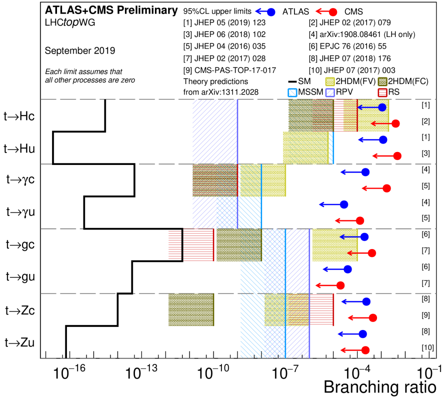
Top Flavor Changing Neutral Currents (FCNCs)

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Table: Branching ratio enhancements in various beyond the standard model theories [Snowmass Top Report]

Top Flavor Changing Neutral Currents

- Current Limits on FCNC Decays



- Limits on $t \to q\gamma$ processes: [JHEP 04 (2016) 035]
  - $t \to \gamma u < 2.8x10^{-5}$
  - $t \to \gamma c < 18x10^{-5}$

Monte Carlo Production of FCNC Signal Samples

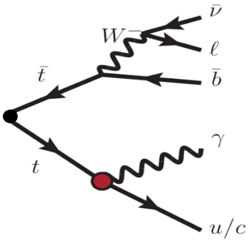
- Due to the low cross sections we must create our own Monte Carlo Samples for our Signal
- An effective field theory approach was taken in the creation of the model [Degrande et al. Phys. Rev. D 91, 034024 (2015)]
- This model takes advantage of dimension-6 operators

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

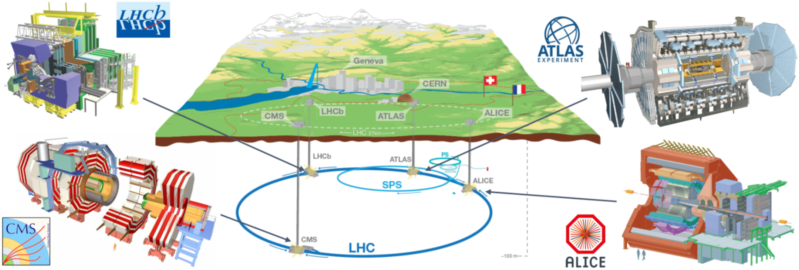
$$\mathcal{L}_{tq\gamma}^{eff} = C\sigma^{\mu\nu} q_\nu (\lambda_{ct}^L P_L + \lambda_{ct}^R P_R) t A_\mu + H.c.$$

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

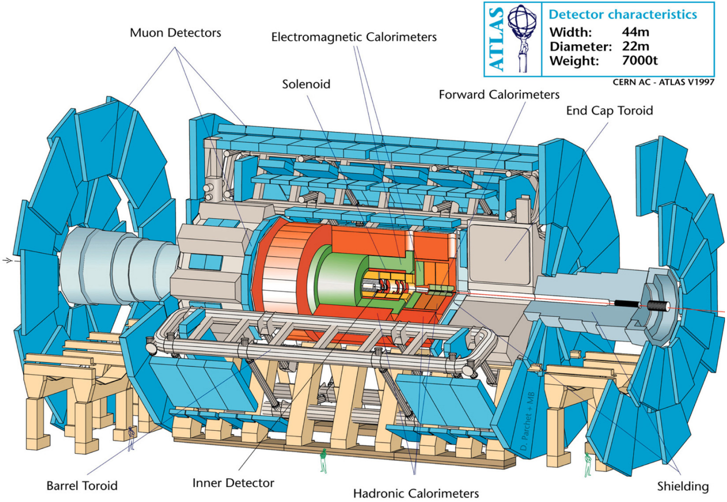


The Large Hadron Collider

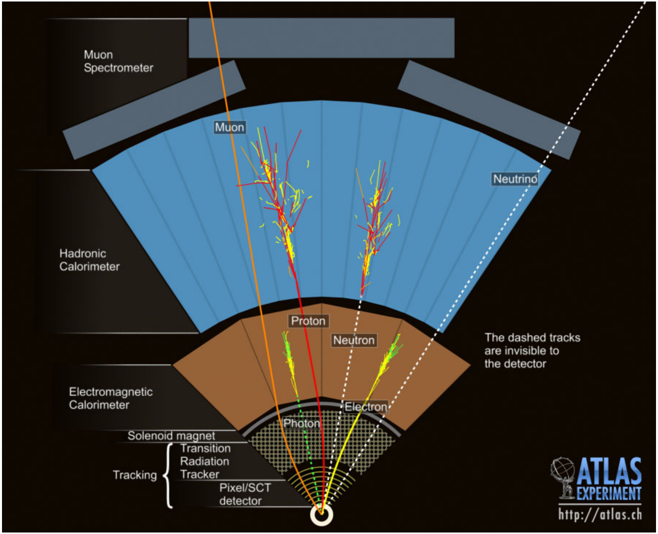


- 27km ring beneath Franco-Swiss border
- Collides protons at center of mass energy 13TeV
- Over 10 Quadrillion (10^{15}) events produced within the ATLAS detector so far

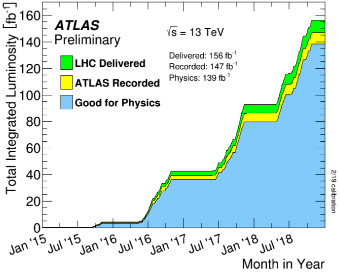
The ATLAS Detector

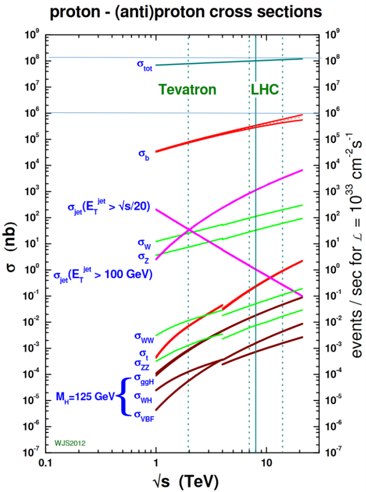


Particles in ATLAS



ATLAS Data

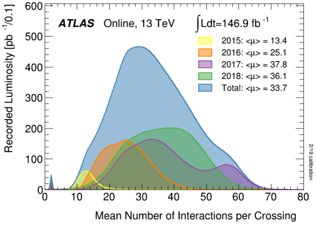


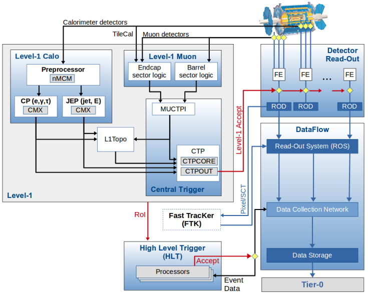


- Total Luminosity at $\sqrt{s} = 13\,TeV$: 139fb^{-1}
- The number of events we see is $N = \sigma L$
- $N_{tot} \approx 14x10^{15}$ events produced during the 13TeV data runs
- $N_{t\bar{t}} \approx 116x10^{6}$

ATLAS Data Acquisition

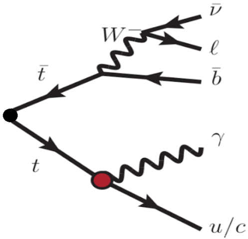
- Average 33.7 collisions per crossing during Run 2, 40MHz collision rate
- Raw uncompressed event: 1.6 MB
- Around 64 TB/s data
- 2 Stage Trigger System
  - Level 1 - Hardware based, coarse object reconstruction, reduces rate to under 100 kHz
  - High-Level Trigger: Software based, performs reconstruction as close to offline as possible, reduces rate to 1 kHz
- Still save 10s of PB per year





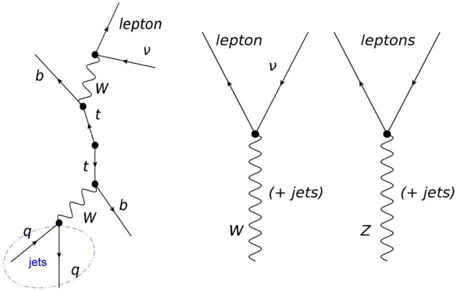
Signal Region Preselection

- Preselect events with objects that look like similar to our expected topology
- Require:
  - Exactly one lepton (e or μ) $\geq$ 25 GeV
  - Exactly one good photon $\geq$ 50GeV
  - Missing transverse energy $\geq$ 30GeV
  - $\geq$ 2 jets (at least 1 b-tag)



Background Processes

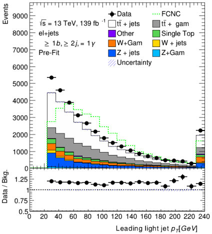
- Due to all of the processes at hadron colliders it is important to model similar event topologies well.
- Major backgrounds include $t\bar{t}$, W+Jets, Z+Jets, + processes with an associated photon

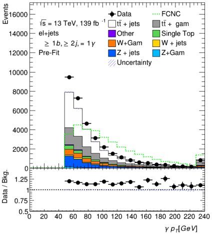


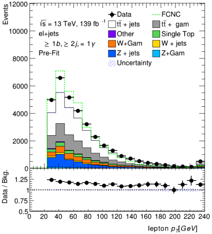
Preselection Objects

- Leading Jet p_T
- Photon p_T
- Lepton p_T

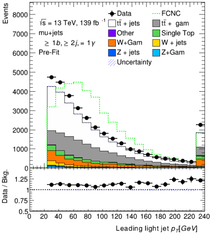
Electron Channel

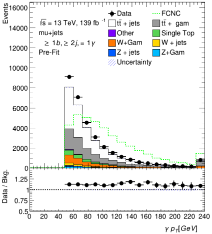


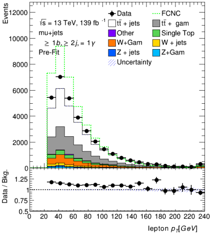




Muon Channel





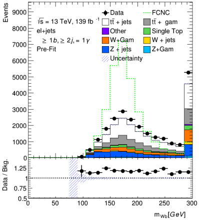


Top Quarks

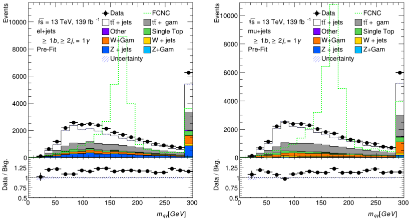
Tops must be reconstructed from these basic physics objects along with b-jets and E_T^{miss}

- Neutrino z-axis direction is ambiguous, determined by minimization of: $\chi^2 = \frac{(m_{b,l,\nu} - m_t)^2}{\sigma^2_{SMtop}} + \frac{(m_{l,\nu} - m_W)^2}{\sigma^2_W}$

SM Top: m_{Wb}



FCNC Top: $m_{q\gamma}$



Additional Processes

- QCD Backgrounds are difficult to model at the energies and interaction rates of the LHC
  - Develop 0 photon regions for scale factors for major backgrounds ($t\bar{t}$ and W+jets)
- Photon misidentification i.e., particles being reconstructed as particles ($e \rightarrow \gamma$, $j \rightarrow \gamma$)
  - $e \rightarrow \gamma$: $Z \rightarrow ee$ tag and probe method used for SF calculation
  - $j \rightarrow \gamma$: ABCD method used for SF calculation

0 Photon Backgrounds

Select events with objects that look like similar to our expected topology for major backgrounds ($t\bar{t}$, W+jets) Require:

- Common Object Selection (MET,Triggers, etc.)
- Exactly one lepton (e or μ) $\geq$ 25 GeV
- Number of Jets to define Regions:
  - W+jets enriched region: $n_{\text{jets}} = 3$
  - Validation Region: $n_{\text{jets}} = 4$
  - $t\bar{t}$+jets enriched region: $n_{\text{jets}} \geq 5$
- Exactly 1 b-tagged jet
- $\geq$ 2 jets (at least 1 b-tag)

Calculate scale factors simultaneously:

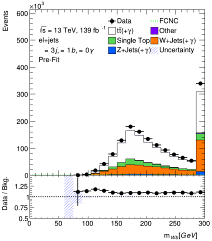
$$\begin{bmatrix} N(W)_{3j} & N(t\bar{t})_{3j} \\ N(W)_{5+j} & N(t\bar{t})_{5+j} \end{bmatrix} \begin{bmatrix} W_{SF} \\ t\bar{t}_{SF} \end{bmatrix} = \begin{bmatrix} N(\text{data-bkg})_{3j} \\ N(\text{data-bkg})_{5j} \end{bmatrix}$$

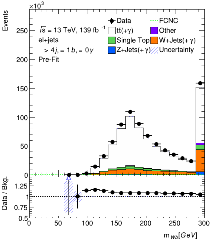
Sample	e+jets SF	μ+jets SF
W+jets	1.22	1.25
$t\bar{t}$	1.06	1.01

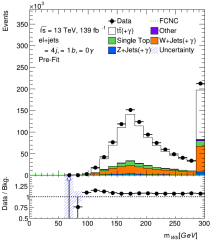
0 Photon Scale Factors, m_{Wb} distributions before SF

- W+jets Enriched
- $t\bar{t}$ Enriched
- Validation Region

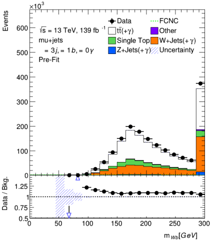
Electron Channel

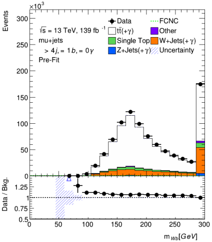


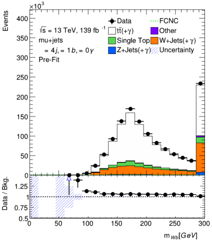




Muon Channel



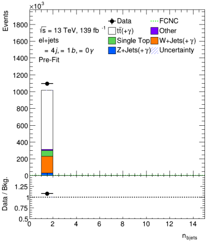


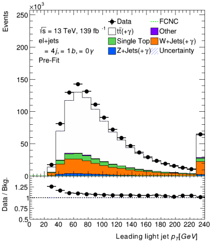


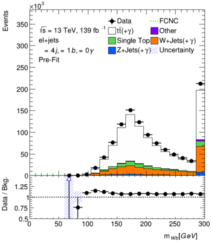
0 Photon Regions: VR before/after SF, electron channel

- n_{bjets}
- Lead Jet p_T
- m_{Wb}

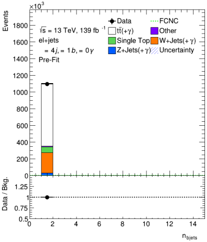
Before SF

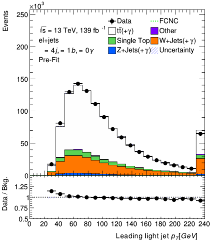


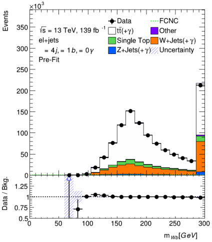




After SF







$e \rightarrow \gamma$ Fake Rate Object Selection

- Want to calculate fake rate in events which could enter the signal region.
- Create 2 control regions: $Z \rightarrow ee$ and $Z \rightarrow e\gamma$
- Require:
  - Common Object Selection (MET,Jets,Triggers, etc.)
  - $Z \rightarrow ee$: 2 Opposite Sign Electrons, 86.1 GeV $< m_{e^+e^-} <$96.1 GeV
  - $Z \rightarrow e\gamma$:1 Electron, $\geq$1 Photon, 86.1 GeV $< m_{e\gamma} <$96.1 GeV
- Tag and Probe Method used

$e \to \gamma$ Scale Factor

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

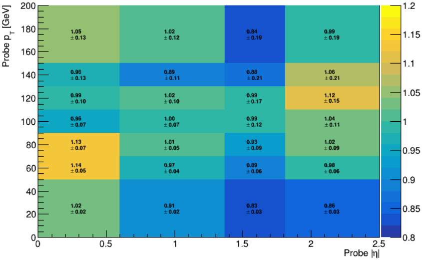
$$\mathrm{SF}_{\mathrm{FR}}^{\text{e-fake}} = \frac{\mathrm{FR}_{\text{data}}^{\text{e-fake}}}{\mathrm{FR}_{\text{MC}}^{\text{e-fake}}}$$

This scale factor is calculated for converted and unconverted photons as well as in bins of η and ϕ

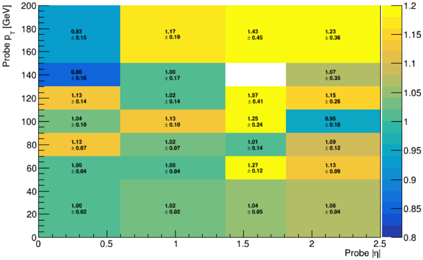
- Converted photons pair produce before the ECAL leaving tracks in the Inner Detector
- Unconverted photons only pair produce inside of the ECAL

$e \to \gamma$ 2D Fake Rates

- Converted γ

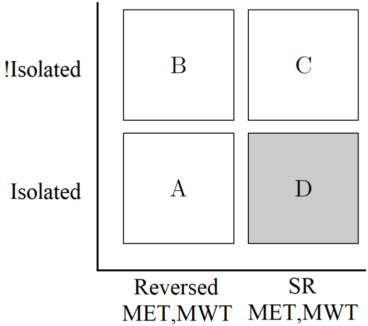


- Unconverted γ



$j \rightarrow \gamma$ Fake Rates

Majority of hadronic fake photons are from $t\bar{t}$ events where a final state jet radiates a non-prompt photon. Similarly radiated photons for W+jets and single top processes can enter the signal region through the radiation of a non-prompt photon.



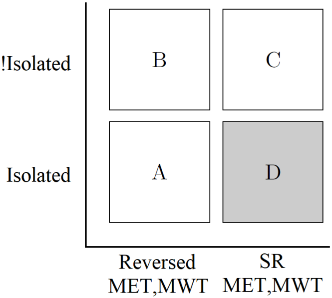
$j \to \gamma$ ABCD Method

$$\frac{N_D^{\text{h-fake}}}{N_C^{\text{h-fake}}} = \frac{N_A^{\text{h-fake}}}{N_B^{\text{h-fake}}} \text{ and } \frac{N_D^{\text{h-fake}}}{N_A^{\text{h-fake}}} = \frac{N_C^{\text{h-fake}}}{N_B^{\text{h-fake}}}$$

Want uncorrelated variables, use a correction factor to account to ensure closure

$$\theta_{\text{MC}} = \frac{N_{\text{D,MC}}^{\text{h-fake}} / N_{\text{C,MC}}^{\text{h-fake}}}{N_{\text{A,MC}}^{\text{h-fake}} / N_{\text{B,MC}}^{\text{h-fake}}}$$

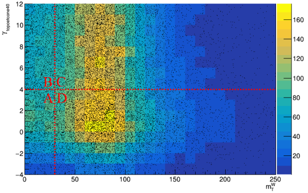
$$N_{\text{D,est.}}^{\text{h-fake}} = \frac{N_{\text{A,data}}^{\text{h-fake}} \times N_{\text{C,data}}^{\text{h-fake}}}{N_{\text{B,data}}^{\text{h-fake}}} \times \theta_{\text{MC}}$$

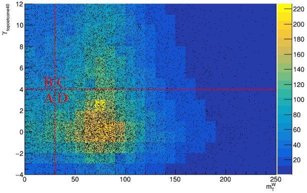


$$\text{SF}^{\text{h-fake}} = \frac{N_{\text{D,est.}}^{\text{h-fake}}}{N_{\text{D,MC}}^{\text{h-fake}}}$$

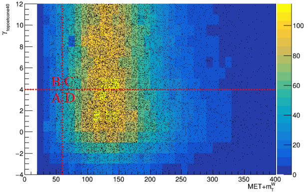
- Converted Photons
- Unconverted Photons

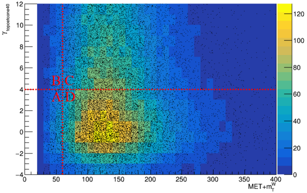
e channel





μ channel



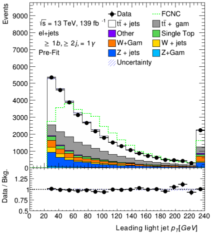


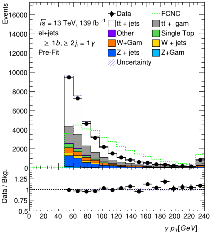
Channel:	Converted	Unconverted
Electron Channel	1.28 ± 0.34	1.99 ± 0.52
Muon Channel	1.23 ± 0.50	2.27 ± 0.92

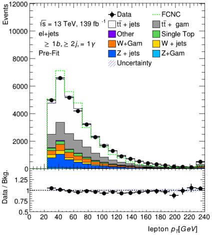
Post SF Preselection Objects

- Leading Jet p_T
- Photon p_T
- Lepton p_T

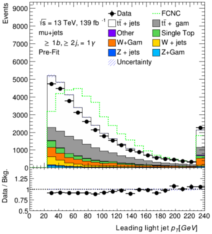
Electron Channel

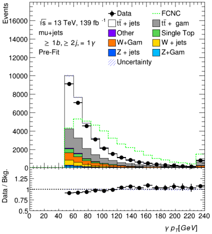


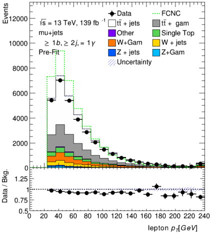




Muon Channel







Neural Networks

- Advanced pattern recognition used to classify events
- A dense neural network is used with various low and high level variable inputs
- Supervised learning used to approximate any multidimensional function

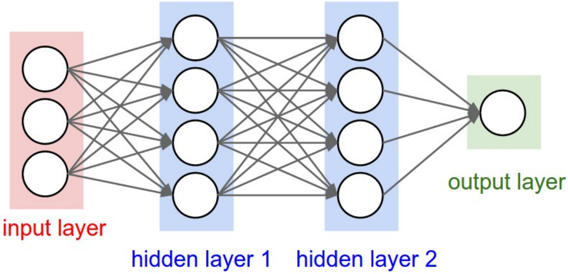


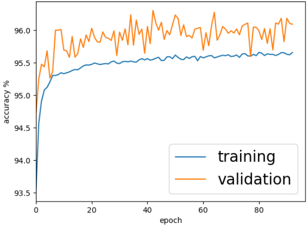
Figure: [Ref: Neural Network]

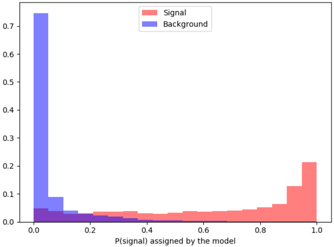
Neural Network Model Inputs

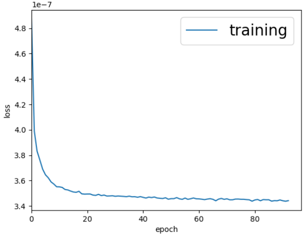
- Using keras on top of tensorflow various network architectures were tested
- Networks are set up with 1 input layer, 2 hidden layers of 10 nodes, and 1 output node
- Each hidden layer has 20% dropout to prevent overtraining by removing codependency between nodes
- Batch size of 100 used and each network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

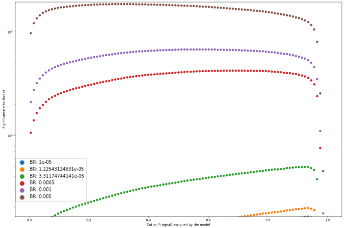
Neural Network Example Outputs

e+jets Channel Example

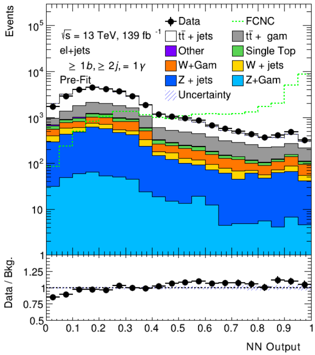


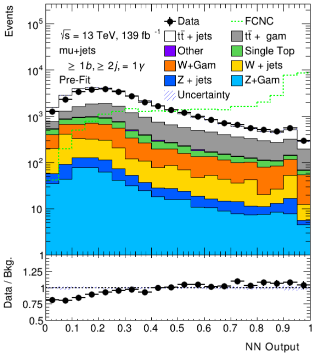






Explain about VRs, closer to SR than preselec Maybe show NN output in VR2

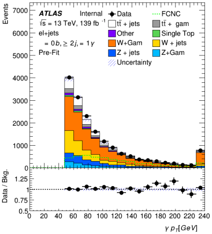


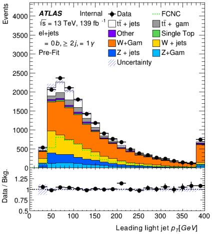


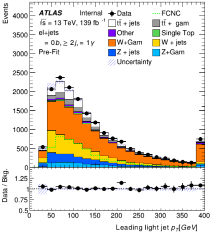
Validation Regions: $W + \text{jets} + \gamma$

- γp_T
- Lead Jet p_T
- m_{Wb}

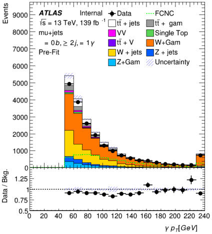
Electron Channel

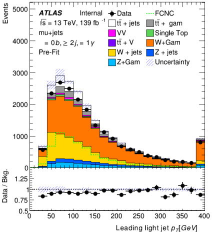


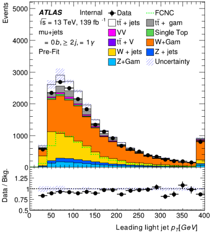




Muon Channel





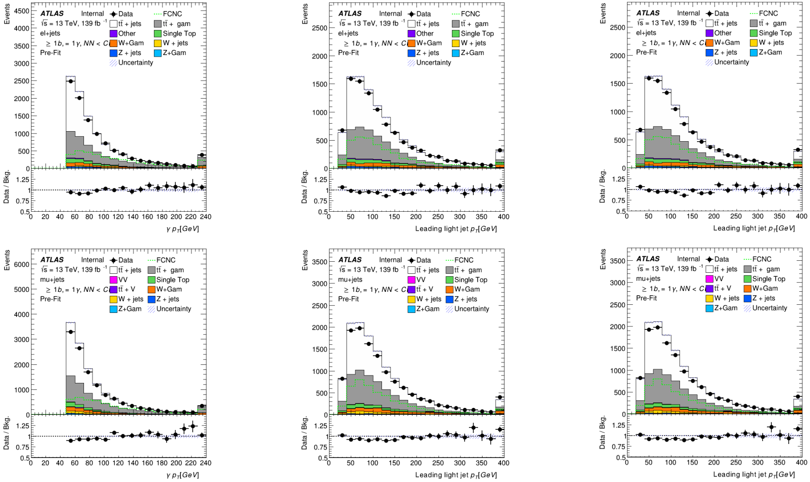


Validation Regions: $t\bar{t} + \text{jets} + \gamma$

- γp_T
- Lead Jet p_T
- m_{Wb}

Electron Channel

Muon Channel

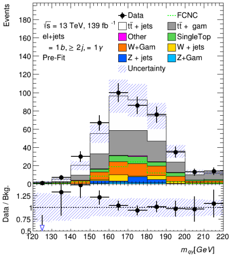


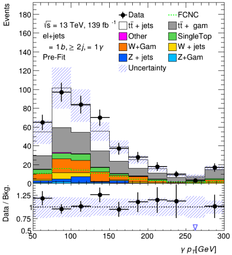
Analysis

Pre-fit Signal Region Plots

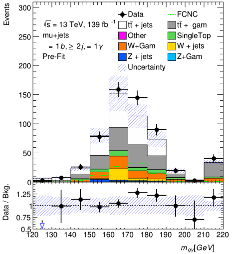
$m_{q\gamma}$ γp_T

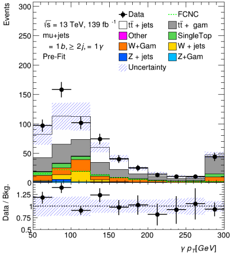
Electron channel





Muon channel



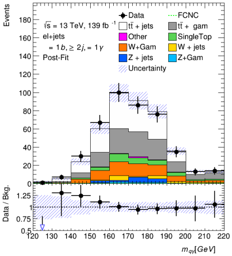


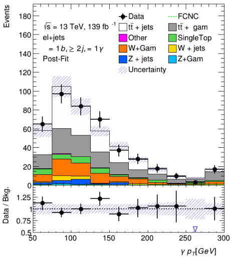
Systematic Uncertainties - Nuisance Parameters

Post-fit Signal Region Plots

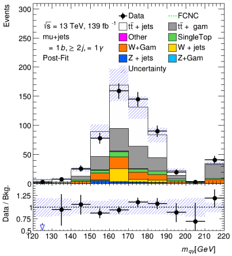
$m_{q\gamma}$ γp_T

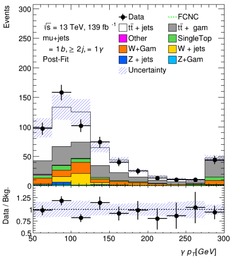
Electron channel





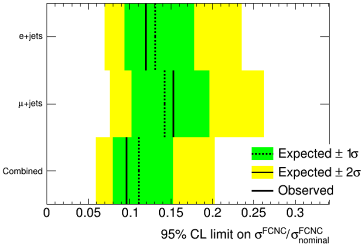
Muon channel





CL_s Method - Limit Setting

Result - Limit on BR($t \to q\gamma$)



Channel	Obs. Limit	Exp. Limit
e+jets	1.19×10^{-4}	$1.31(^{+0.47}_{-0.36}) \times 10^{-4}$
μ+jets	1.53×10^{-4}	$1.42(^{+0.51}_{-0.39}) \times 10^{-4}$
Combined	0.96×10^{-4}	$1.10(^{+0.43}_{-0.30}) \times 10^{-4}$

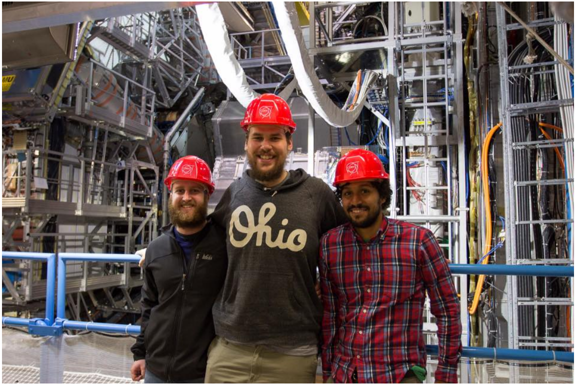
Conclusions

- Limits have been set on the process $t \rightarrow q\gamma$
- Neural network implementation improved result by up to 30% compared to stats only improvement

Thank You

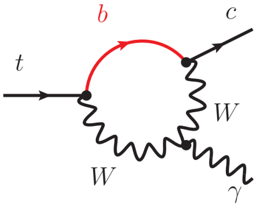
Special thank you to my committee:
David Strom (Chair)
Spencer Chang
Dev Sinha
My Advisor: Jim Brau

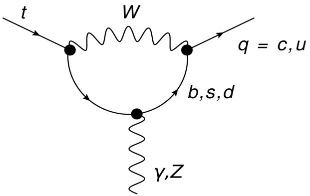
Questions?



Backup

FCNC Diagrams





Neural Network Model Inputs

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

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

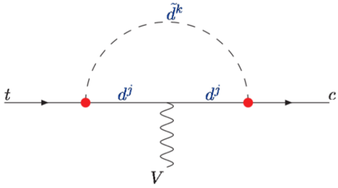
Input Variables

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

A Couple BSM Diagrams

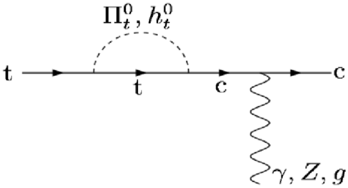
- R-parity-violating supersymmetric models

  [arXiv:hep-ph/9705341]



- Top-color-assisted technicolor models

  [arXiv:hep-ph/0303122]



Jets/AntiKT

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

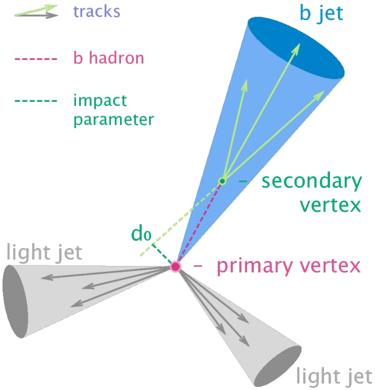
$$d_{iB} = \frac{1}{p_{ti}^2}$$

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

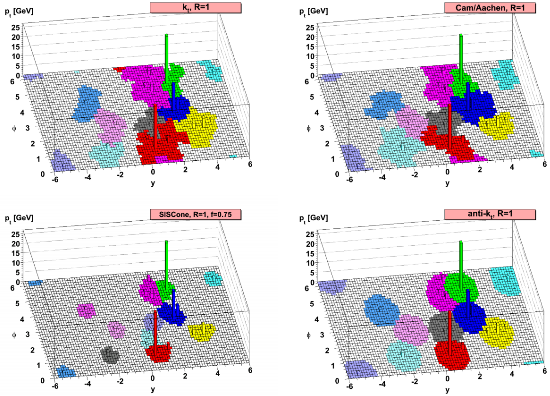
- Find minimum of entire set of $\{d_{ij}, d_{iB}\}$
- If d_{ij} is the minimum particles i,j are combined into one particle and removed from the list of particles
- If d_{iB} is the minimum i is labelled as a final jet and removed from the list of particles
- Repeat until all particles are part of a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

B-tagging

- B Hadrons travel a measureable distance before decay
- Tracks originate from outside of interaction point (Seconday 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



Jet Algorithms



- IR Safety: Adding soft emission particle does not change final jet configuration
- Collinear Safety: Splitting a jet into 2 collinear jets yields the same result, jet size does not matter

Jet Algorithms

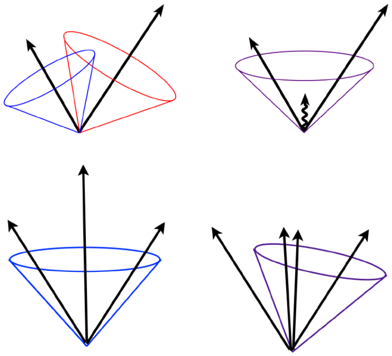
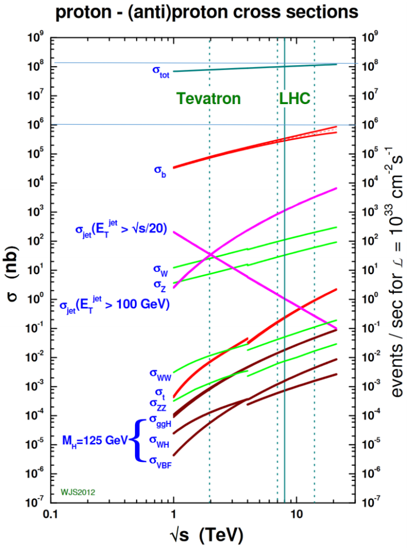


FIGURE 4.4. Illustration of the infrared sensitivity of a cursory designed jet algorithm (top). Illustration of the product of a collinear unsafe jet algorithm. A collinear splitting changes the number of jets (bottom). [52].

Courtesy - John Myers

What's in the data?



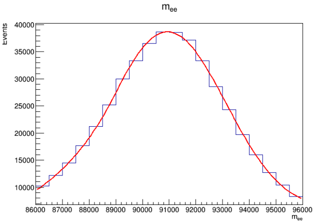
- The number of events we see is $N = \sigma L$
- $\sigma_{t\bar{t}} = 831.76\text{pb}$
- $N_{t\bar{t}} \approx 116x10^6$
- $N_{tot} \approx 14x10^{15}$ events produced during the 13TeV data runs

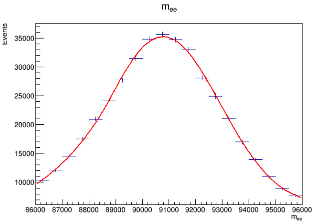
m_{ee}, $m_{e\gamma}$

egamma fake rate Data and MC

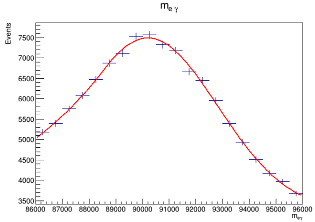
- Data
- Monte Carlo

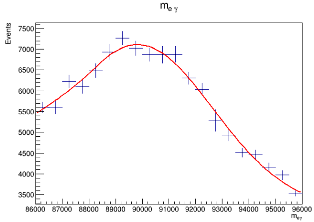
m_{ee}





$m_{e\gamma}$

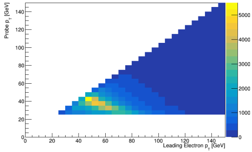


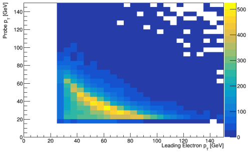


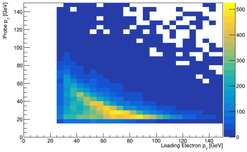
$e \rightarrow \gamma$ Data and MC Distributions

- Probe e
- Converted γ
- Unconverted γ

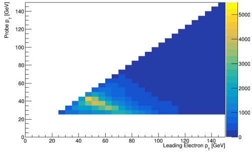
Data

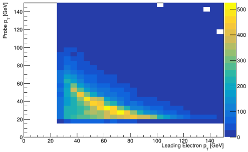


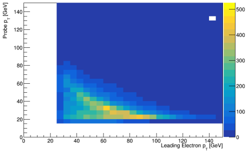




MC







Neural Network Optimizers

- Various optimization functions can be used, I make use of Adam (Adaptive Moment Estimation)
  - Adam computes adaptive learning rates for every parameter and stores a history of the parameters used to calculate the next step
  - Stores first (mean) and second (uncentered variance) moments of the gradients used during training
  - Converges very fast and is less computationally intensive

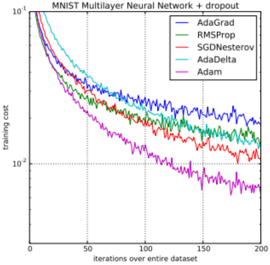
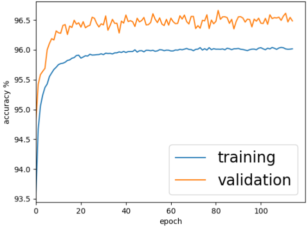
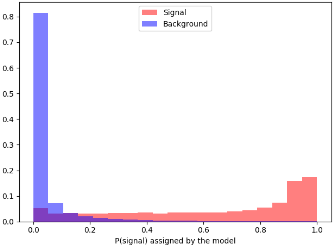


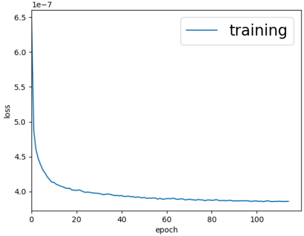
Figure: [Ref:Machine Learning Mastry]

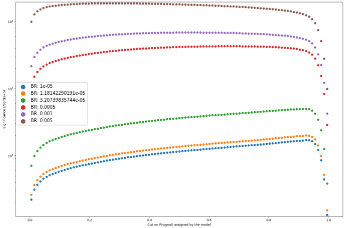
Neural Network Example Outputs

mu+jets Channel Example









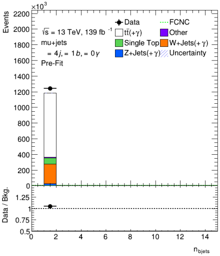
Duplicate Event Removal

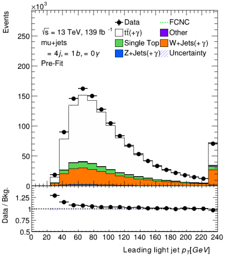
$$\mathcal{L}_{tq\gamma}^{eff} = -e\bar{c}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}(\lambda_{ct}^{L}P_L + \lambda_{ct}^{R}P_R)tA_{\mu} + H.c.$$

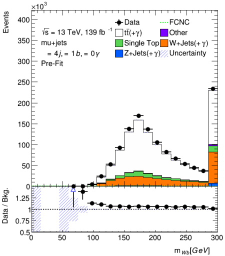
0 Photon Regions: VR before/after SF, muon channel

- n_{bjets}
- Lead Jet p_T
- m_{Wb}

Before SF







After SF