

SEARCH FOR THE FLAVOR-CHANGING NEUTRAL CURRENT IN TOP
PAIR EVENTS WITH AN ASSOCIATED PHOTON USING 13 TEV
PROTON-PROTON COLLISION DATA COLLECTED WITH THE ATLAS
DETECTOR

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DISSERTATION ABSTRACT

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Additional ATLAS Collaboration publications can be found:
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CHAPTER I

INTRODUCTION

The Standard Model of particle physics has proven itself an exceptional and resilient theory since the combination of the electromagnetic and weak interactions in 1961[1]. Further theoretical work combined the Higgs Mechanism[2, 3] with the electroweak theory[4, 5]. The resiliency of this theoretical model has been tested to further degrees of accuracy over the decades with one of the most recent test being the experimental confirmation of the Higgs Boson in 2012[6, 7] using the Large Hadron Collider (LHC). Further precision measurements are ongoing at various experiments at the LHC, including the ATLAS experiment.

However, the Standard Model is known to have flaws and disagreements with nature. For example, the Standard Model predicts massless neutrinos which is in conflict with experimental observation of neutrino flavor oscillation and does not provide an explanation for dark matter particles or their interactions with currently known particles. While these large gaps in the Standard Model are well known, every precision measurement made has yet to give any significant new hints toward physics beyond the Standard Model. One new pathway to look for these hints at the LHC is through top quark decays.

1.1. The Standard Model Top Quark

The top quark was first observed at Fermilab's Tevatron in 1995[8] but the increase in energy and amount of data at the LHC has produced orders of magnitude more top quarks than previously seen, opening up a pathway to precision measurements of the properties of the top quark. The top quark is the heaviest

fundamental particle with a mass of 172.51 ± 0.27 (stat) ± 0.42 (syst)[9]. This large mass also means that the top quark lifetime is very short ($5 * 10^{-25}$ s) and decays before it can hadronize. This allows the study of its branching ratios and decay modes directly. The Standard Model predicts that the top quark decays through the charged current mode nearly 100% of the time, $t \rightarrow qW$ ($q = b, s, d$)[10]. The Standard Model also predicts a rare branching ratio of the top quark through a flavor changing neutral current (FCNC) process, to a neutral boson (photon, Z boson, Higgs Boson, or gluon) and up type quark with a heavily suppressed branching ratio on the order of 10^{-14} [11].

1.2. Searching for FCNC Top Quark Decays

Precision measurements are an important litmus test for the Standard Model. Predicted branching ratios for FCNC processes in top quark decays are far beyond the experimental reach of the LHC and any observation of these decay modes would be a sure sign of new physics. Branching ratios are an important measurement due to a litany of theories for new physics beyond the Standard Model (BSM). These BSM theories such as Minimal Supersymmetric models[12], R-parity-violating Supersymmetric models[13] and two Higgs doublet models[14] predict enhancements in the top sector by many orders of magnitude. Even a null result of a search will set an upper limit on the branching ratio that can assist in ruling out future physical models based on their amount of large top sector enrichment.

This dissertation presents a search for top FCNCs using the entire Run 2 dataset at the LHC, containing combined 2015-2018 datasets taken by the ATLAS experiment totaling 139 fb^{-1} of integrated luminosity taken at $\sqrt{s} = 13 \text{ TeV}$. This analysis looks for an excess of events coming from top quark pair produced events where one top

quark decays to the most likely decay mode (a bottom quark and W boson) and the other to an up type quark (up or charm) and a photon. Chapter II presents a theoretical background for the Standard Model with a closer view on the usual extensions to include the FCNC vertices. Following this, Chapter III will discuss the LHC and the ATLAS experiment used in the creation of the dataset used in the analysis. In Chapter IV the special signal simulation requirements will be presented as well as the common background event simulation methodology. The search strategy including the creation of signal, control and validation regions and the training of a neural network will be examined in Chapter V. Chapter VI will discuss the results and the conclusions drawn from these results will be presented in Chapter VII.

CHAPTER II

THEORY

In this chapter a theoretical background will be presented on the Standard Model of particle physics with special attention paid to the top quark's properties and decays. This will include discussion of all of the fundamental particles and their interactions through the fundamental forces of nature: electromagnetism and the strong and weak nuclear forces.

2.1. The Standard Model Particles

The Standard Model of particle physics is the cornerstone of our understanding of the basic building blocks of nature and their interactions. Typical matter is made up of atoms consisting of electrons around an inner nucleus of protons and neutrons. These protons and neutrons are made up of a collection of up and down type quarks along with sea quarks and gluons. Protons consist of two up type quarks and a down type quark, while neutrons contain two down type quarks and a single up type quark.

Within the Standard Model all matter (quarks and leptons) is made up of fermions (spin- $\frac{1}{2}$ particles). In addition to the up and down type quarks and the electron the remaining fermions can be described as additional 'generations' that are similar, each consisting of two quarks and a lepton. Every generation consists of quarks with electric charge $+\frac{2}{3}$ and $-\frac{1}{3}$ and a lepton with charge -1 along with an electrically neutral lepton called a neutrino. All of these fermions are listed in Table 2.1.

While we can observe the leptons in nature, free quarks do not exist. We can observe quarks only as part of a bound state called a hadron. If a hadron consists of a

quark-antiquark pair ($q\bar{q}$) it is called a meson. Sets of three quarks or three antiquarks (qqq or $\bar{q}\bar{q}\bar{q}$) are called baryons. Protons and neutrons are baryonic matter.

In addition to the fermions the Standard Model contains gauge, or vector, bosons which are spin-1 particles that carry the fundamental forces of nature. The electromagnetic force is mediated by the massless, charge neutral photon (γ). The nuclear weak force is carried by two massive bosons: the electrically neutral Z boson and the charged (± 1) W boson. These bosons together dictate electroweak interactions within the Standard Model. The remaining force, the nuclear strong force, is carried through the gluon (g). Gluons are massless and chargeless but carry color, an analog of electric charge in the electroweak interaction. The last remaining piece of the Standard Model is the scalar (spin-0) Higgs boson. This Higgs boson is a massive electrically neutral boson that is responsible for giving mass to the massive fundamental particles. All of these bosons are also shown in Table 2.1.

	Particle	Spin	Charge	Mass
Quarks				
u type	u			$2.4^{+0.6}_{-0.4}$ MeV
	c	$\frac{1}{2}$	$\frac{2}{3}$	1.28 ± 0.03 GeV
	t			173.1 ± 0.6 GeV
d type	d			$4.7^{+0.5}_{-0.4}$ MeV
	s	$\frac{1}{2}$	$-\frac{1}{3}$	96^{+8}_{-4} MeV
	b			$4.18^{+0.04}_{-0.03}$ GeV
Leptons				
e doublet	e	$\frac{1}{2}$	-1	$0.5109989461 \pm 0.000000003$ MeV
	ν_e		0	< 2 eV
μ doublet	μ	$\frac{1}{2}$	-1	$105.6583745 \pm 0.0000024$ MeV
	ν_μ		0	< 2 eV
τ doublet	τ	$\frac{1}{2}$	-1	1776.86 ± 0.12 GeV
	ν_τ		0	< 2eV
Bosons				
Vector	γ	1	0	$< 10^{-18}$ eV
	g	1	0	0
	W	1	\pm	80.385 ± 0.0015 GeV
	Z	1	0	91.1876 ± 0.0021 GeV
Scalar	H	0	0	$125.09 \pm 0.21 \pm 0.11$ GeV

TABLE 2.1. Particles of the Standard Model [10]

2.2. The Standard Model Interactions

In addition to describing these particles the Standard Model also describes the ways in which these particles are capable of interacting. All of the particles described in the previous section are included in the following theory. The Standard Model Lagrangian is simply a function of fields and their derivatives taken at one point in spacetime, x^μ .

$$\mathcal{L}[\phi_i(x), \partial_\mu \phi_i(x)]$$

The Standard Model is defined having a gauge symmetry

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

Name	Field Components	$(SU(3)_C, SU(2)_L, U(1)_Y)$	Comments
Spin-1/2 Quarks			
Q	$(u_L \ d_L)$ u_R d_R	$(3,2,\frac{1}{6})$ $(3,1,\frac{2}{3})$ $(3,1, -\frac{1}{3})$	x3 generations
Spin-1/2 Leptons			
L	$(\nu_L \ e_L)$ e_R	$(1,2,-\frac{1}{2})$ $(1,1,-1)$	x3 generations
Spin-0 Higgs			
ϕ	$(\phi^+ \ \phi^0)$	$(1,2,\frac{1}{2})$	
Spin-1 Gauge Bosons			
Gluons	$G^{1,...,8}$	$(8,1,0)$	
W	$(W^1 \ W^2 \ W^3)$	$(1,3,0)$	
B	B^0	$(1,1,0)$	

TABLE 2.2. Summary of the Standard Model field contents and their representations in the gauge group, labeled by their dimension ($SU(3)_C$ and $SU(2)_L$) and weak hypercharge ($U(1)_Y$)

where all of the particle content described in Section 2.1 is described under this symmetry in Table 2.2[15]. The eight color-anticolor combinations of spin-1 gluons are associated with $SU(3)_C$ where the C denotes 'color' quantum numbers of the gauge group. Any particle that carries color will interact with gluons via the strong nuclear interaction. The three spin-1 gauge bosons W_a , $a = 1, 2, 3$ conduct the weak isospin $SU(2)_L$ symmetry where the L denotes that only left-handed chiral fermions transform with respect to this symmetry. The left-handed fermions are $SU(2)$ doublets while the right-handed components are singlets. The remaining spin-1 gauge boson, B, is associated with $U(1)^Y$ weak hypercharge.

The W^\pm , Z , and photon (γ) are produced by spontaneous symmetry breaking $SU(2)_L \times U(1)_Y$ implied by the Higgs potential discussed Section 2.3.

One general way of expressing the Standard Model Lagrangian is

$$\mathcal{L}_{SM} = \mathcal{L}_{kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

where we have a kinetic term for the bosons and fermions, a Higgs term which includes the Higgs kinetic term and potential, and a term that dictates the Yukawa interactions. This can be expanded out

$$\mathcal{L} = \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \text{h.c.} \right) + (|D_\mu \phi|^2 + V(\phi)) + (\psi_i Y_{ij} \psi_j \phi + \text{h.c.})$$

All of the gauge field strengths are included within $F_{\mu\nu}$. To maintain gauge invariance for the kinetic terms the derivative must be replaced by the covariant derivative

$$\partial^\mu \rightarrow D^\mu = \partial^\mu + ig_s G_a^\mu L_a + ig W_a^\mu T_a + ig' B^\mu Y$$

The eight gluon fields are described by G_a^μ , the three weak interaction boson fields are described by W_a^μ , and the hypercharge boson field is B^μ . Here g_s , g , and g' are the gauge coupling constants, and L_a , T_a , and Y are the generators for $SU(3)_C$, $SU(2)_L$, and $U(1)_Y$ respectively. The generators are described by the Gell-Man matrices for L_a ($\frac{1}{2}\lambda_a$ for triplets, 0 for singlets), the Pauli matrices for T_a ($\frac{1}{2}\sigma_a$ for doublets, 0 for singlets), and the $U(1)_Y$ charges for Y .

2.3. Electroweak Symmetry Breaking

The spin-1 particles within the Standard Model are massless; however we know that the real bosons made up of these states are massive (i.e. the W^\pm and Z). This comes about from a spontaneous symmetry breaking of $SU(2)_L \times U(1)_Y$ by a particle

whose ground state is not invariant under the symmetry. The scalar Higgs field is capable of doing this while at the same time not breaking the $SU(3)_C$ symmetry leaving the gluons massless because ϕ is an $SU(3)_C$ singlet.

Expanding the Yukawa term of the Lagrangian we see that the covariant derivative of the scalar field becomes

$$D_\mu \phi = \partial_\mu \phi - \frac{i}{2} (g W_\mu^a \frac{\sigma^a}{2} + g' B_\mu) \phi$$

and the potential

$$V(\phi) = \lambda (\phi^\dagger \phi - \frac{\mu^2}{2\lambda})^2 = \lambda (\phi^\dagger \phi)^2 - \mu^2 \phi^\dagger \phi + \frac{\mu^4}{4\lambda}$$

It follows that if $\frac{\mu^2}{\lambda} > 0$ then this potential has a non-zero vacuum expectation value $v^2 \equiv \frac{\mu^2}{\lambda}$. The condition $\lambda > 0$ is a requirement on the vacuum stability of the model such that $\mu^2 < 0$ is the requirement for spontaneous symmetry breaking. Therefore we can make a gauge transformation such that

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

2.3.1. Gauge Boson Masses

The mass eigenstates of the spin-1 bosons can be recovered from this by writing out the mass part of the gauge boson kinetic term $|D^\mu \phi|^2$

$$\mathcal{L}_{mass} = -\frac{1}{8} \begin{pmatrix} 0 & v \end{pmatrix} \begin{pmatrix} gW_3 + g'B & g(W_1 - iW_2) \\ g(W_1 + iW_2) & -gW_3 + g'B \end{pmatrix}^2 \begin{pmatrix} 0 \\ v \end{pmatrix}$$

and if we define the weak mixing angle as $\tan\theta_W \equiv \frac{g'}{g}$ and the mass eigenstates of the bosons

$$W^\pm \equiv \frac{1}{\sqrt{2}}(W_1 \mp iW_2)$$

$$Z \equiv \cos\theta_W W_3 - \sin\theta_W B$$

$$A \equiv \sin\theta_W W_3 + \cos\theta_W B$$

then the mass matrix can be diagonalized to give

$$\mathcal{L}_{mass} = -\frac{1}{4}g^2 v^2 W^+ W^- - \frac{1}{8}(g^2 + g'^2)v^2 Z^2$$

which gives us the masses of our bosons: $M_W^2 = \frac{1}{4}g^2 v^2$, $M_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$, and $M_A^2 = 0$. Since the field A is massless there is an unbroken $U(1)$ that is identified as the photon and $U(1)_{EM}$.

2.3.2. Fermion Masses

Fermions acquire their masses from the Yukawa term in the Lagrangian. If we transform into the mass basis, also using the replacement of the scalar field corresponding to a physical Higgs boson

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

then we can write the $SU(2)_L$ quark doublets into their components

$$Q_{Li} = \begin{pmatrix} U_{Li} \\ D_{Li} \end{pmatrix}$$

The Yukawa term can be broken down into a baryonic and leptonic portion. The lepton portion leads to charged lepton masses after the Higgs acquires a vacuum expectation value after electroweak symmetry breaking.

$$-\mathcal{L}_{\text{Yukawa}}^{\text{leptons}} = Y_{ij}^e \overline{L}_{Li} \phi E_{Rj}$$

This leads to three physical parameters, which are generally chosen to be the three charged lepton masses (electron, muon, tau). The baryonic term leads to quark masses and flavors. Ten physical parameters arise from the baryonic Yukawa interactions

$$-\mathcal{L}_{\text{Yukawa}}^{\text{quarks}} = Y_{ij}^d \overline{Q}_{Li} \phi D_{Rj} + Y_{ij}^u \overline{Q}_{Li} \tilde{\phi} U_{Rj} + \text{h.c.}$$

Expanding this in terms of the above $SU(2)_L$ components

$$-\mathcal{L} = (M_d)_{ij} \overline{D}_{Li} D_{Rj} + (M_u)_{ij} \overline{U}_{Li} U_{Rj} + \text{h.c.}$$

such that $M_q = \frac{v}{\sqrt{2}} Y^q$. Unitary matricesies (V_{qL} and V_{qR}) that take us to the mass basis can always be found.

$$V_{qL} M_q V_{qR}^\dagger = M_q^{\text{diag}}, \text{ for } q=u,d$$

The quark mass eigenstates that follow from this are:

$$q_{Li} = (V_{qL})_{ij} q_{Lj}^I \text{ and } q_{Ri} = (V_{qR})_{ij} q_{Rj}^I$$

being transformed from the interaction basis I .

2.3.3. The CKM Matrix

In the interaction basis interactions between quarks and W^\pm come from the $\bar{\psi}D\psi$ kinetic term in the Lagrangian. We can explicitly write this out in both the interaction and mass basis such that:

$$\text{Interaction Basis: } -\mathcal{L}_{W^\pm}^q = \frac{g}{2} \overline{Q}_{Li} \gamma^\mu W_\mu^a \tau^a Q_{Li} + \text{h.c.}$$

$$\text{Mass Basis: } -\mathcal{L}_{W^\pm}^q = \frac{g}{\sqrt{2}} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} \gamma^\mu (V_{uL} V_{dL}^\dagger)_{ij} W_\mu^+ \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

The term $V = V_{uL} V_{dL}^\dagger$ in the previous equation is a unitary 3×3 matrix known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix [16, 17] that describes quark mixing.

The CKM matrix can be expressed simply:

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

The components of the CKM matrix are not all arbitrary. This can be expressed in the Wolfenstein parametrization[18] to show that there are only four parameters, three real and one complex. The Wolfenstein parameterization is an expansion in $V_{us} = \lambda = 0.2257^{+0.009}_{-0.0010}$. Where $A = 0.814^{+0.021}_{-0.022}$, $\rho = 0.135^{+0.031}_{-0.016}$, and $\eta = 0.349^{+0.015}_{-0.017}$ [10].

$$V_{CKM}^{\text{Wolfenstein}} = \begin{bmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

This formulation demonstrates quite clearly that the CKM matrix is almost diagonal but has small off-diagonal terms. This means that interactions between quarks is strongest within a generation i.e. up and down quarks, charm and strange quarks, and top and bottom quarks experience the largest degree of mixing between each other. A top quark directly decays to a bottom quark and W boson almost all of the time ($\approx 99.83\%$ of the time). While the mixing does not prohibit decaying to a strange or down quark instead of a bottom, it is a significantly rarer event ($\approx 0.16\%$ and $\approx 0.01\%$, respectively). The values for all of these parameters have been measured experimentally and are collected by the Particle Data Group[10]:

$$V_{CKM} = \begin{bmatrix} 0.97420 \pm 0.00021 & 0.2243 \pm 0.0005 & 0.00394 \pm 0.00036 \\ 0.218 \pm 0.004 & 0.997 \pm 0.017 & 0.0422 \pm 0.0008 \\ 0.0081 \pm 0.0005 & 0.0394 \pm 0.0023 & 1.019 \pm 0.025 \end{bmatrix}$$

2.4. The Top Quark

This dissertation will pay particular interest to the top quark, the heaviest of all of the fundamental particles, over 40 times heavier than its generational partner the bottom quark and 40% larger than the Higgs boson the next heaviest particle. One of its most interesting properties, due to its large mass, is that it has an extremely small lifetime ($\approx 5 \times 10^{-25}s$). This lifetime is orders of magnitude shorter than the characteristic time over which the strong nuclear interaction takes place ($\approx 10^{-23}s$), meaning that it decays before it can hadronize by combining with another quark to form a mesonic or baryonic system. This allows us to observe the decays of the top quark directly as opposed to the decay products of a top quark system. The top quark was first proposed as an explanation of CP violation in kaon decays by

Kobayashi and Maskawa in 1973[17] which predicted a third generation of quarks. At the time there was little evidence for this. The later discovery of the charm quark, that was predicted to exist due to a suppression caused by the GIM mechanism[19], and formed the foundation of Kobayashi and Maskawa's work provided further evidence. The discovery of the charm filled out a complete 2 generation Standard Model (up, down, strange, and charm quarks and the electron and muon). However the further observation of the tau lepton meant that the symmetry between lepton and quark generations would be broken without the existence of a third generation of quarks, the top and bottom, providing soft evidence of a third generation of quarks. Within just a few years, in 1977, the bottom was also discovered[20] and the theoretical predictions of the Standard Model at the time heavily favored the existence of a 6th quark, the 3rd and heaviest up-type quark.

2.4.1. Discovering The Top Quark

Almost 20 years went by after the discovery of the bottom quark and many experiments came up empty handed even while discovering the W and Z bosons (the Super Proton Synchrotron at CERN) before direct evidence for the top quark was observed at Fermilab's Tevatron in both the CDF and D0 experiments in 1995[8, 21]. While the Tevatron only operated at a maximum energy of 1.96 TeV during its lifetime, further properties of the top quark could not be probed in detail due to a lack of statistics. Not until the LHC began operation at a center of mass energy of 7 TeV in 2010 were enough top quarks produced to study the details of its interactions.

The amount of top quarks produced scale up by the energy as seen in Figure 2.1 as well as the integrated luminosity, or number of events produced, of the accelerator

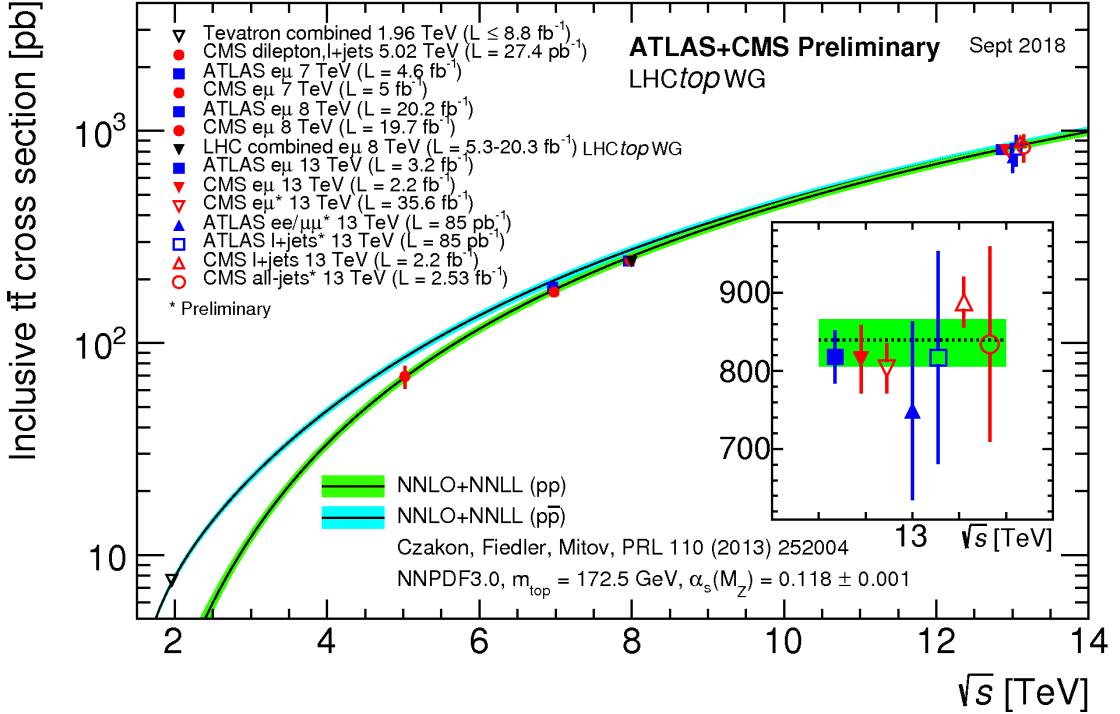


FIGURE 2.1. Summary of $t\bar{t}$ production cross sections as a function of center of mass energy at Fermilab’s Tevatron and CERN’s LHC. For a top mass of 172.5 GeV and center of mass energy of 13 TeV the central value cross section is calculated to be 831 pb [22]

and detector setup. The LHC has significantly more of both than the Tevatron did. Throughout the entirety of Run 2 at the LHC there are expected to be more than 115,000 top pair events produced within the ATLAS detector, allowing physicist to probe the details of the top quark better than ever before.

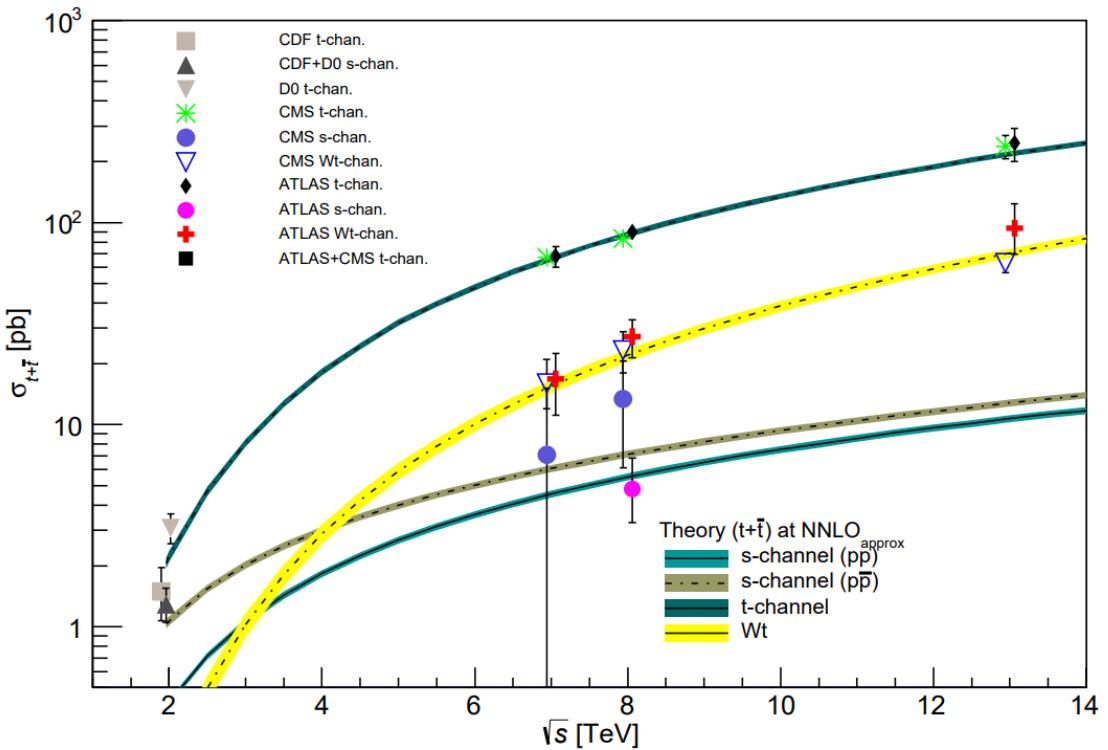


FIGURE 2.2. Summary of single-top production cross sections as a function of center of mass energy at Fermilab’s Tevatron and CERN’s LHC[22]

2.4.2. Production and Decay At Hadron Colliders

There are multiple ways to produce top quarks at the LHC. The most prevalent production mechanism of top quarks is through producing top/anti-top quark pairs. This can be done, to leading order, either by quark-antiquark annihilation (Figure 2.3a) or gluon gluon fusion (Figure 2.3b-d). At the Tevatron, a proton anti-proton collider, the leading diagram was quark-antiquark annihilation because of the significantly larger amount of antiquarks in the collisions. At the LHC the major production mechanism is gluon-gluon fusion, $\approx 90\%$, while quark-antiquark annihilation accounts for only $\approx 10\%$ of top quark pair production. This is a strong interaction process and is therefore quite common. The cross sections are shown in Figure 2.1.

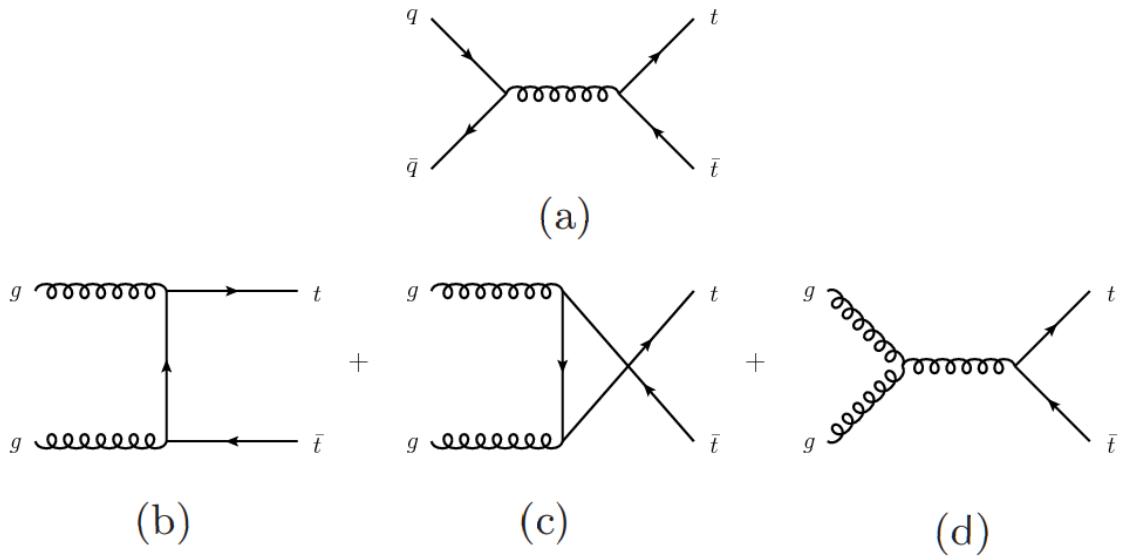


FIGURE 2.3. Leading order diagrams for the production of top/anti-top quark pairs at hadron colliders. Quark-antiquark annihilation diagram in (a) while (b)-(d) show various gluon-gluon fusion diagrams

Single top quarks can also be produced through weak interactions, which is less common, and the leading diagrams are shown in Figure 2.4 and their cross sections as measured at the LHC and Tevatron are shown in Figure 2.2. Comparing the leading production mechanisms at 13 TeV, it can be seen that $t\bar{t}$ production is about a factor of 4 larger than single top production. This means there are about 8x as many top quarks looking at pair produced events, as two are produced per event while giving an additional experimental handle in looking for an invariant mass of final state products around the top quark mass.

Because the top quark decays before hadronization, we can study the branching ratios to various products directly. Figure 2.5 shows ways the top quark is allowed to decay in the Standard Model. Figure 2.5a shows the most likely decays where the top quark decays to a down-type quark and a W boson. The branching ratio of these decays is proportional to the square of the corresponding matrix element in the CKM

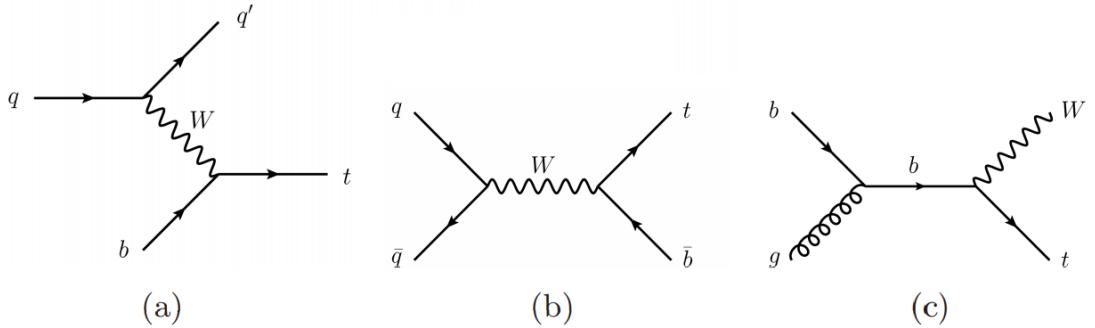


FIGURE 2.4. Leading order diagrams for the production of single top quarks at hadron colliders. The t-channel diagram is shown in (a), the s-channel in (b), and production in association with a W-boson is shown in (c)

matrix as shown in Section 2.3.3. The sum of these branching ratios is unity within standard error bars such that the implication of the diagrams, corresponding to the flavor-changing neutral current decays, shown in Figure 2.5b, are highly suppressed which will be explored further in Section 2.5.

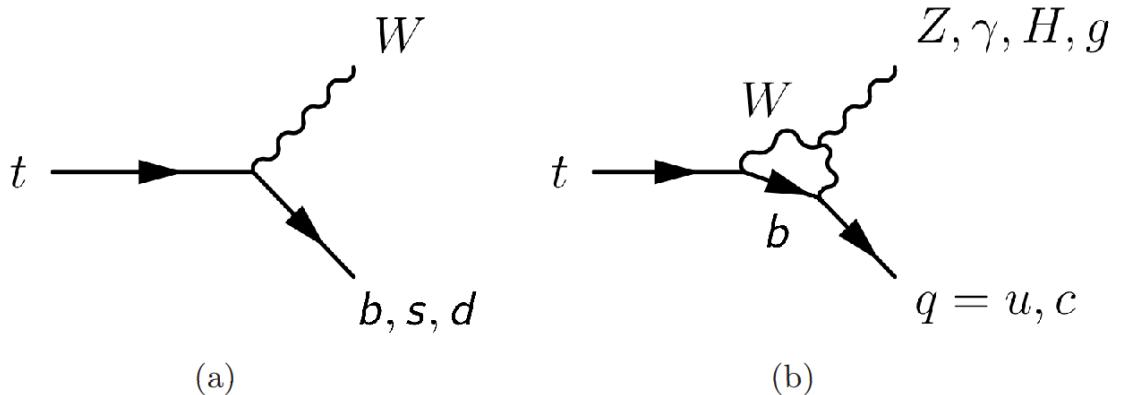


FIGURE 2.5. Top quark decays in the Standard Model

Since the matrix element V_{tb} in the CKM matrix is essentially unity each top usually decays to a b quark and a W boson. The final state of the top pair events are then typically categorized by the decay of the W bosons. The W boson can decay leptonically to a lepton (electron, muon, or tau) and its associated

Decay Mode	States	Decay Mode	States	Decay Mode	States
$W^+ \rightarrow e^+ \nu_e$	1	$W^+ \rightarrow u\bar{d}$	$\times 3 V_{ud} ^2$	$W^+ \rightarrow c\bar{d}$	$\times 3 V_{cd} ^2$
$W^+ \rightarrow \mu^+ \nu_\mu$	1	$W^+ \rightarrow u\bar{s}$	$\times 3 V_{us} ^2$	$W^+ \rightarrow c\bar{s}$	$\times 3 V_{cs} ^2$
$W^+ \rightarrow \tau^+ \nu_\tau$	1	$W^+ \rightarrow u\bar{b}$	$\times 3 V_{ub} ^2$	$W^+ \rightarrow c\bar{b}$	$\times 3 V_{cb} ^2$

TABLE 2.3. Summary of final states of a W^+ boson, when accounting for color permutations and the CKM matrix. The table holds true if you flip all particles to their antiparticles

neutrino or hadronically to quarks. This means top pair events are described as "all-hadronic" when both W bosons decay hadronically, "leptonic" if both W bosons decay leptonically, or "semi-leptonic" if one W boson decays hadronically and the other leptonically. The ratios of these events is shown in Figure 2.6. However, because of how the tau decays and interacts, these events are typically treated separately. Only the electron and muons are considered as the leptons in the "semi-leptonic" final state of a $t\bar{t}$ event. A quick counting (neglecting final state particle masses) of the final states of W bosons is shown in Table 2.3. The unitarity condition of the CKM matrix implies that $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. The phase space of the final product then has 1 state for each of the leptons and approximately 3 for each of the up type quarks so a single top quark can be expected to decay into a lepton $\approx \frac{3}{9}$ of the time or any combination of quarks the other $\approx \frac{6}{9}$ of the time. This holds when looking at the branching ratios of top quark pairs in Figure 2.6. The end result of this is that the regions of special interest for this dissertation, the electron and muon semi-leptonic final states, occur $\approx 30\%$ of the time. While this is not the largest selection of the final state branching ratios the presence of a lepton makes it easier to look for these final states.

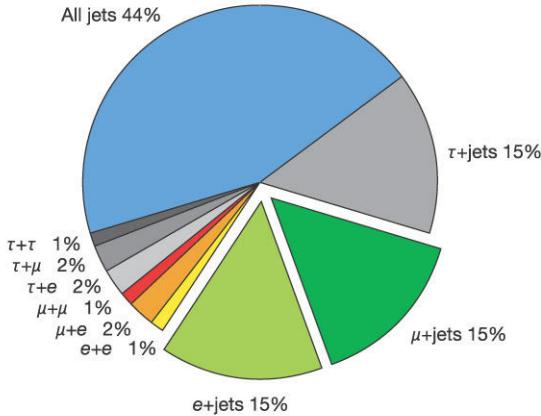


FIGURE 2.6. Categorization of top quark pair decays in the Standard Model based on the decays of the W bosons[23]

2.4.3. Beyond the Standard Model Top Quark Physics

Many questions remain open with the intricacies of the Standard Model involving top quarks. The mass of the top quark is at a mass scale similar to the W, Z, and Higgs bosons. Does this imply the top plays a special role in the mechanism of electroweak symmetry breaking? After the discovery of the Higgs: why do the top quark and Higgs boson have the exact masses they do which allows the electroweak potential to be stable up to very high energy scales as well as allowing the Universe to sit in a meta-stable state[24]? Because of its large mass the top quark is the main destabilizer of the Higgs potential. It may be possible that new physics models will predict phenomena that can be more easily found in the properties of the top quark due to changes in the Higgs sector. Many new physics models will present most dramatically in top quarks as radiative corrections to new massive particles will affect tops first before presenting in deviations in properties of the other, significantly lighter, fermions. For example, a new Higgs like particle would most likely couple most strongly to the top quark. Now that an unprecedented number of top quarks

events are accessible, the predictions of the Standard Model can be tested with much greater precision. Top quark production modes, decay modes, couplings, and various other properties are now being measured and providing limits on the phase spaces of any new physical models that exist or ruling out entire classes of models that have yet to be written down. Arguably the properties of top quark are one of the most likely places that will point to a new understanding of our Universe.

2.5. The Flavor-Changing Neutral Current

The idea of "flavor" in the Standard Model refers to copies of the $SU(3)_C \times U(1)_{EM}$ representation, shown previously in Table 2.2. Specifically it will be used in the discussion of the generational change of one quark into another through some interaction. As an example, Figure 2.5b shows a flavor-changing neutral current interaction.

2.5.1. The Standard Model Flavor Sector

Quarks that interact with W^\pm bosons have interactions that stem from the kinetic term of the Standard Model Lagrangian. If this is written out explicitly in the mass eigenstates the interaction looks like:

$$-\frac{g}{\sqrt{2}} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} \gamma^\mu W_\mu^+ V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

where the W interacts directly to change the flavor of quarks from an down(up)-type to an up(down)-type quark. The CKM matrix can be thought of as a rotation between the mass and interaction basis and the fact that the CKM matrix is non-

diagonal means that the W boson interacts with quarks of different generations. The small off-diagonal elements of the CKM matrix mean that this generational change is a significantly smaller effect than interactions that change flavors within a generation, e.g. a top quark going to a bottom quark and W boson is much more likely than a top quark decaying to a down or strange quark and a W boson. Going two generations away from the diagonal the mixing from the CKM matrix is even smaller. The interaction with a W boson between two quarks is the only interaction vertex in the Standard Model that allows for both flavor and generation changes.

As opposed to this flavor changing charged current interaction the FCNC is an interaction between neutral gauge bosons and fermions. These FCNC processes involve either up or down type quarks or involve charged or neutral leptons. The flavor of the fermion is changed but the electric charge is conserved because it interacts with a neutral boson as opposed to the W^\pm like in the charged current interaction. FCNC interactions are forbidden at tree-level in the Standard Model but can occur via higher order processes such as loops (as shown in Figure 2.5b).

There are four neutral bosons in the Standard Model: the gluon, photon, Higgs boson, and Z boson. Each of these can mediate FCNC interactions but all are forbidden at tree-level. The gluon and photon correspond to exact gauge symmetries and have diagonal, flavor universal couplings since their interactions with fermions come through the kinetic terms. The ramification of this is that they only interact with fermions of the same flavor. The Standard Model Higgs cannot couple to fermions of different flavor since the Standard Model fermions are chiral and the Higgs couplings to fermions align with the fermion mass matrix. In the Standard Model there is only a single Higgs doublet and the only source of the fermionic masses is the Higgs vacuum expectation value. The Z boson can only connect to quarks from the

same type (up or down). When you move from the interaction to the mass eigenstates the rotation matrices only include terms such as $U_{uL}U_{uL}^\dagger = 1$ as opposed to the CKM matrix terms ($U_{uL}U_{dL}^\dagger$) which means these couplings are also flavor universal. The Standard Model FCNC suppression is built in through these means as opposed to generation-changing charged current processes. The charged current processes rely on the CKM parameters which are free parameters of the Standard Model and as such are measured and "put in." These FCNCs are suppressed multiple ways in the Standard Model.

2.5.2. The GIM Mechanism

Historically the original Cabibbo model of particle physics only had three quarks: the up, down, and strange. Studies of Kaon decay during the late 1960's suggested there were no neutral current interactions in the Standard Model at the time. The decay $K^+ \rightarrow \mu^+\nu_\mu$ was observed but the process $K_L^0 \rightarrow \mu^+\mu^-$ which was predicted was not observed. Even in the absence of a tree level decay the K_L^0 decay was still predicted via a box diagram through the exchange of W bosons shown in Figure 2.7.

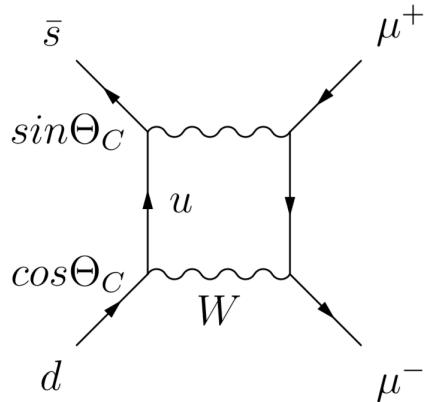


FIGURE 2.7. Box diagram of $K_L^0 \rightarrow \mu^+\mu^-$ through the exchange of W bosons

Interactions at the time were thought to have strangeness quantum number interactions that changed strangeness in the following way:

$$\Delta S = 0 : u\bar{u} + d\bar{d}\cos^2\Theta_C + s\bar{s}\sin^2\Theta_C$$

$$\Delta S = 1 : (s\bar{d} + d\bar{s})\sin\Theta_C\cos\Theta_C$$

The non-observation of the predicted decay led Glashow, Iliopoulos, and Maiani to predict the existence of a fourth quark, the charm, in 1970[19]. The addition of the charm led to two quark doublets and an almost perfect cancellation between the box diagrams:

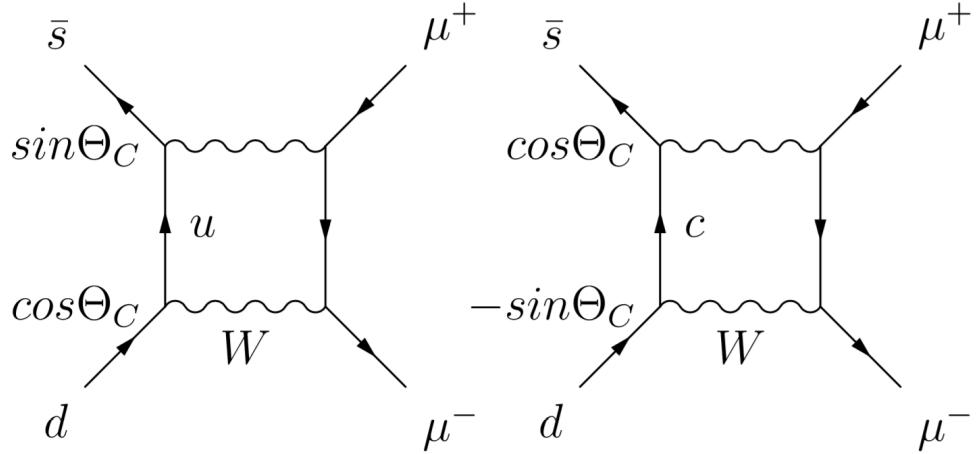


FIGURE 2.8. Box diagrams of $K_L^0 \rightarrow \mu^+\mu^-$ through the exchange of W bosons after the inclusion of the charm quark

These box diagrams mean that the strangeness change in interactions can be rewritten as

$$\Delta S = 0 : u\bar{u} + c\bar{c} + (d\bar{d} + s\bar{s})\cos^2\Theta_C + (s\bar{s} + d\bar{d})\sin^2\Theta_C$$

$$\Delta S = 1 : (s\bar{d} + d\bar{s} - d\bar{s} - s\bar{d})\sin\Theta_C\cos\Theta_C$$

The addition of the charm means that, in the approximation $m_c = m_u$, the $\Delta S = 1$ terms cancel exactly, as the new box diagrams show in Figure 2.8. The FCNC interactions in top quark decays are suppressed through this mechanism as well, with the further inclusion of the bottom and top quarks. They are further suppressed by being proportional to the quark mixing of off-diagonal elements in the CKM matrix, which are significantly less than 1. A loop diagram for top quark FCNC is shown in Figure 2.9. This loop process is very rare. The Standard Model branching ratio for these top FCNC interactions are shown along predicted enhancements from a variety of models of physics beyond the Standard Model in Table 2.4.

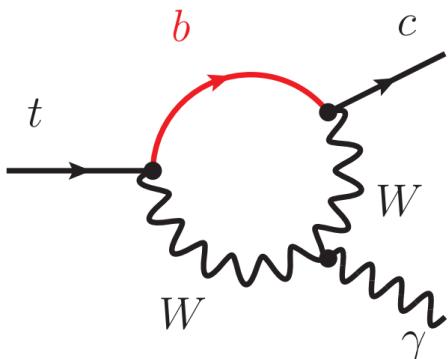


FIGURE 2.9. An example loop diagram of a top quark decaying to a light quark and a photon

Process	SM	2HDM	QS	MSSM	RPV	XD
$t \rightarrow u\gamma$	$4 * 10^{-16}$	—	$\leq 4 * 10^{-8}$	$\leq 10^{-8}$	$\leq 10^{-9}$	—
$t \rightarrow c\gamma$	$5 * 10^{-14}$	$\leq 10^{-7}$	$\leq 4 * 10^{-8}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \rightarrow uZ$	$7 * 10^{-17}$	—	$\leq 6 * 10^{-4}$	$\leq 10^{-7}$	$\leq 10^{-6}$	—
$t \rightarrow cZ$	$1 * 10^{-14}$	$\leq 10^{-6}$	$\leq 6 * 10^{-4}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \rightarrow ug$	$4 * 10^{-14}$	—	$\leq 9 * 10^{-7}$	$\leq 10^{-7}$	$\leq 10^{-6}$	—
$t \rightarrow cg$	$5 * 10^{-12}$	$\leq 10^{-4}$	$\leq 9 * 10^{-7}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \rightarrow uH$	$2 * 10^{-17}$	$\leq 6 * 10^{-6}$	—	$\leq 10^{-5}$	$\leq 10^{-9}$	—
$t \rightarrow cH$	$3 * 10^{-15}$	$\leq 2 * 10^{-3}$	—	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

TABLE 2.4. Expected branching ratios for various flavor-changing neutral current processes in the Standard Model[11] and multiple theories that predict enhancements to the branching ratio. Two-Higgs Double Models with flavor-violating Yukawa couplings (2HDM) [11, 25], quark single models (QS) [26, 27], minimal supersymmetry models with 1TeV squarks and gluinos (MSSM) [12], R-parity violating supersymmetry models (RPV) [28], and extra-dimensional models (XD) [29].

2.5.3. New Physics With Enhancements to FCNCs

Various theoretical models that include physics beyond what is included in the Standard Model are proposed to solve problems that exist with the Standard Model or an explanation of known phenomena that are not in agreement with the Standard Model. Various models seek to solve different problems, e.g., providing a dark matter candidate or fixing the naturalness problem of the Standard Model resulting from an unexpectedly high amount of fine-tuning from loop corrections to the Higgs mass. Top quark FCNCs in the Standard Model are currently so far from experimental reach (≈ 10 orders of magnitude) that they are impossible to observe even with major improvements to the accelerator and detector technologies. Table 2.4 also shows a variety of theories beyond the Standard Model which predict large enhancements to FCNC top couplings. For the most part these enhancements come from terms that have very heavy particles moving in the loops. Therefore searching for FCNCs

with top quarks provides a particularly good handle to study models of new physics and rule out the phase spaces of these models by lowering the expected limit. An explanation of the various models explored in Table 2.4 follows.

Two-Higgs-Doublet Models (2HDM): 2HDM are a simple extension of the Standard Model which contain two Higgs doublets instead of the one currently contained in the Standard Model. This leads to a much richer phenomenology in the Higgs sector with two CP even neutral Higgs bosons (h and a heavier H), a CP odd pseudoscalar A , and two charged Higgs bosons H^\pm . The currently discovered Higgs boson can be mapped to either h or H depending on various limits in the model of choice. These models can typically be described by an additional six parameters: the four Higgs masses (m_h, m_H, m_A, m_{H^\pm}), the ratio of the two vacuum expectation values and a mixing angle that diagonalizes the mass matrix of the neutral CP even Higgs bosons. Many supersymmetric models predict the existence of an extra Higgs doublet. Some of these models also attempt to explain the baryon asymmetry of the Universe[30]. 2HDM Models predict very large enhancements to FCNC interactions due to an extension of the electroweak symmetry breaking sectors. Some of these models (type III 2HDM, and models of minimal flavor violation) include tree level FCNCs[31] which is why the enhancement brings the branching ratio up to an observable level.

Quark Singlet Models (QS): QS involve an extension to the Standard Model in the form of an extra vector-like quark singlet that couples strongly to the top quark, typically in the form of a top-partner quark. These heavier t' quarks could explain the fine-tuning of the Higgs boson mass through cancellation of some or all of the top loop diagrams present in the radiative corrections to the Higgs mass. These models

generally imply then that the CKM matrix is no longer unitary and tree level FCNCs are allowed which offers a great enhancement to potential branching ratios[26, 27].

Minimal Supersymmetric Models (MSSM): Supersymmetric models where every Standard Model particle has a super particle partner typically aim to solve multiple problems with the Standard Model at once. In general the lightest supersymmetric particle, which is stable, provides a good dark matter candidate. MSSM models have super partner quarks (squarks) and super partner gluons (gluinos) on a mass scale of ≈ 1 TeV. Top FCNCs can occur through loop diagrams still, as they do in the Standard Model, but the loop is enhanced as it includes the supersymmetric particle of the top quark (the heavier stop quark)[12, 32].

R-Parity Violating Supersymmetric Models (RPV): Another supersymmetric model R parity is no longer conserved because all superpartners are odd under the parity. FCNCs can also occur at the one loop level in these models in loops which no longer conserve baryon or lepton number.[28]

Extra-dimensional Models (XD): XD Models are Randall-Sundrum models that describe the Universe as a warped-geometry higher dimensional space where elementary particles are localized on a (3+1)-dimensional brane. These models offer a potential solution to the hierarchy problem of the Standard Model by adding in a mechanism to explain the difference between the typical scales over which FCNCs take place (the electroweak scale) and the Planck scale. In these models FCNCs exist due to flavor-violating couplings between Standard Model fermions and Kaluza-Klein excitations of the gauge bosons in the Standard Model[29]. Due to their overlap in the extra dimension with Kaluza-Klein gauge modes the flavor-violating couplings will be largest in the top sector.

2.5.4. Current Measurements of Top FCNCs

All four of the neutral boson mediated FCNC channels can be searched for individually and model independently. Each channel will have its own signature and various advantages and disadvantages in performing the search. Each of the potential tree-level diagrams is shown in Figure 2.10, all of which are forbidden at tree level in the Standard Model.

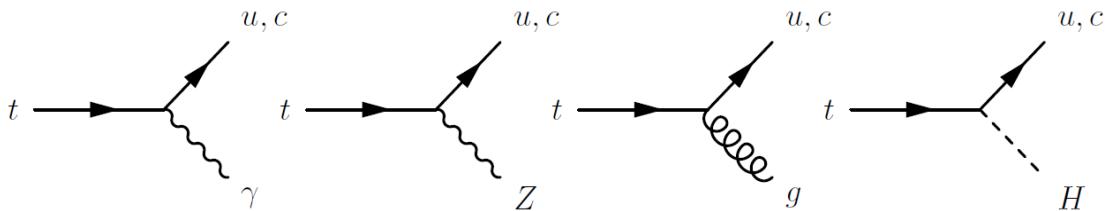


FIGURE 2.10. Flavor-changing neutral current top quark decays.

The FCNC channels involving all of the various neutral bosons can be searched for with the ATLAS detector in both single-top production modes as well as the decay mode through $t\bar{t}$ events. All of the production channels provide a sharp separation between $u \rightarrow tX$ and $c \rightarrow tX$ but have fewer events than searching in the decay mode using $t\bar{t}$ events. Some final states of these various FCNC events such as those involving the decay mode search for $t \rightarrow qZ$ exploit the tri-lepton final state ($Z \rightarrow ll$, with the other top decaying leptonically $t \rightarrow bW \rightarrow bl\nu$). The FCNC process involving the Higgs boson has the advantage of being able to look in a wide range of potential final states of the Higgs and can be successfully tackled using a variety of different methods.

Limits have been set on these FCNC processes at various experiments in the past. The electron-proton collider HERA at DESY, the electron-proton collider LEP at CERN, and the proton-proton colliders the Tevatron at Fermilab and the LHC at

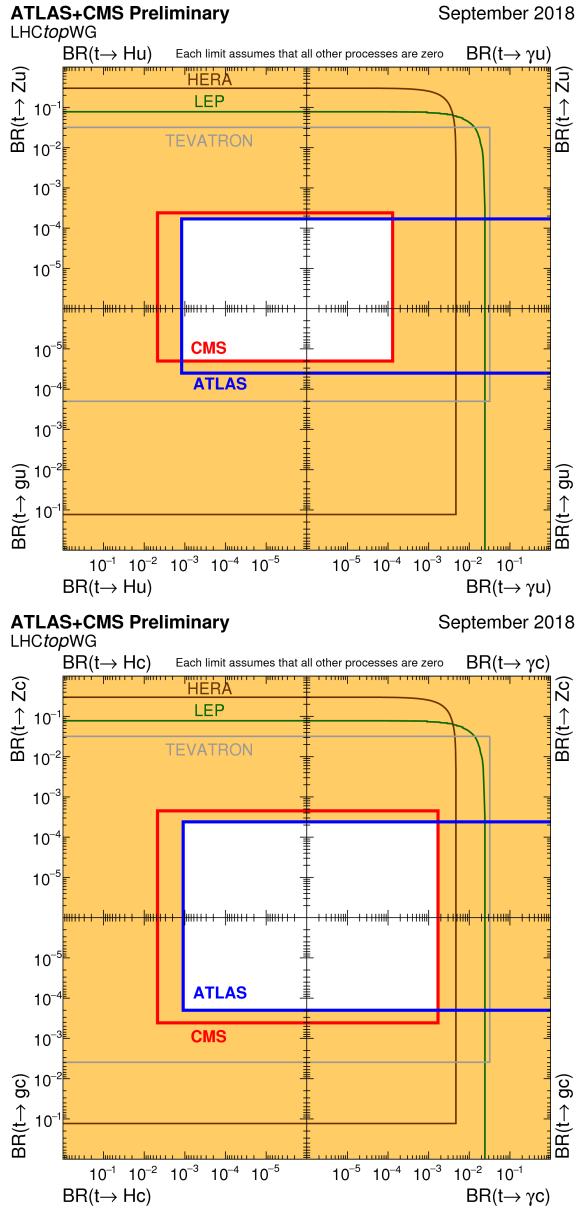


FIGURE 2.11. Flavor-changing limits from a variety of experiments in every channel $t \rightarrow uX$ (top) and $t \rightarrow cX$ (bottom) [22]

CERN have all had experiments searching for the FCNC processes. The collected limits of these experiments are shown in Figure 2.11. Due to the energy of these early colliders 209 GeV center of mass energy for LEP and 318 GeV for HERA only production modes could be searched for as they are below the production threshold

for $t\bar{t}$ pairs. The diagrams searched for at these experiments are shown in Figure 2.12 (HERA) and Figure 2.13 (LEP).

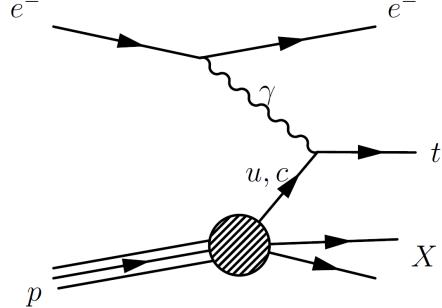


FIGURE 2.12. FCNC diagram for the search in single top production at the electron-proton collider HERA.

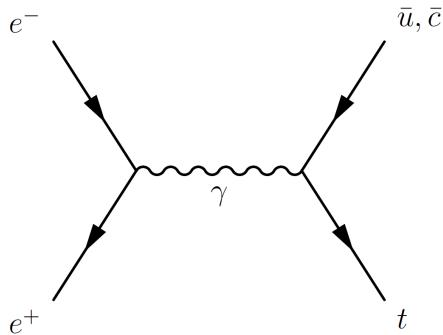


FIGURE 2.13. FCNC diagram for the search in single top production at the electron-positron collider, LEP.

Shown in Figure 2.14 are the Standard Model theoretical predictions, various beyond the Standard Model predictions (as discussed in Section 2.5.3), and experimental limits for all processes $t \rightarrow Xq$ where q is an up-type quark and X is any neutral boson.

Since the publication of Figure 2.14 the ATLAS experiment has published a result in the production mode of the $t \rightarrow q\gamma$ vertex using 81 fb^{-1} of data (LHC data runs between 2015-2017). Upper limits have been set on $t \rightarrow u\gamma$ left-handed (right-handed) branching ratio of 2.8×10^{-5} (6.1×10^{-5}) and upper limits on $t \rightarrow c\gamma$

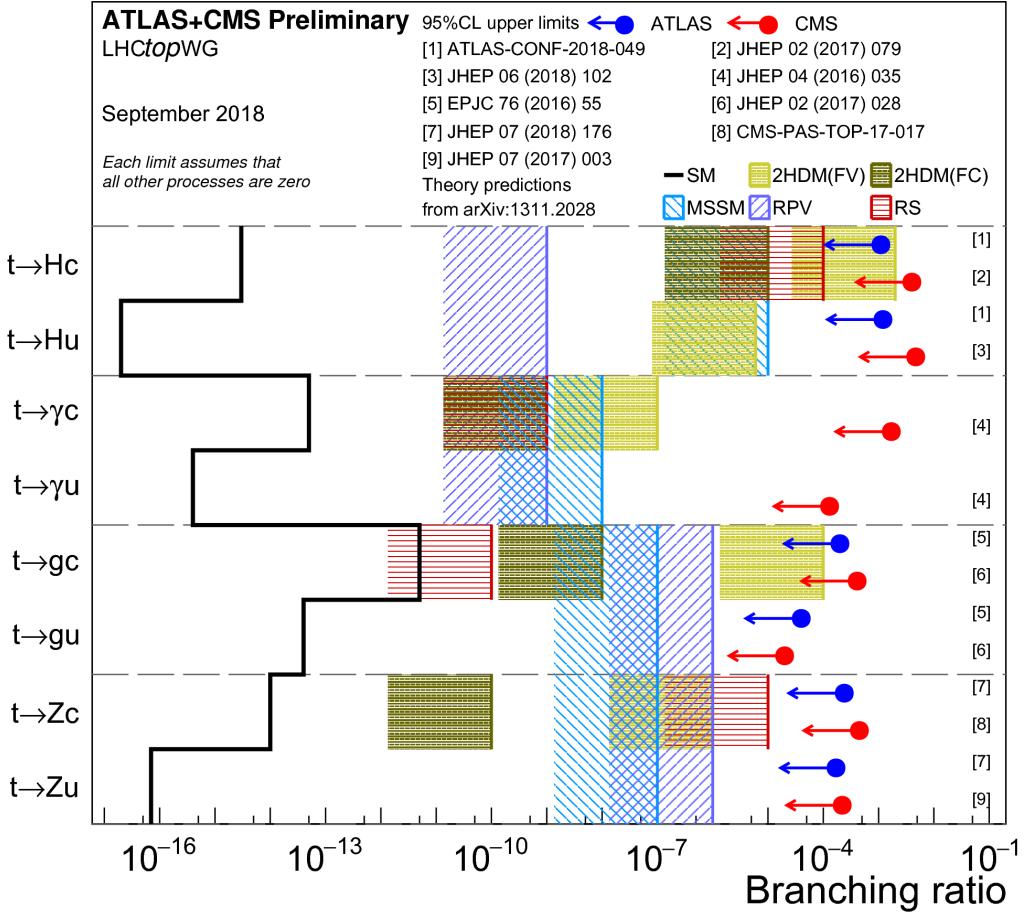


FIGURE 2.14. Flavor-changing neutral current theoretical branching ratios and experimental limits (both ATLAS and CMS) updated through 2018 [22]

left-handed (right-handed) branching ratio of 22×10^{-5} (18×10^{-5}) [33]. Production mode searches offer better reach for $t \rightarrow u\gamma$ over $t \rightarrow c\gamma$ due to the higher prevalence of up quarks in the parton distribution function of the colliding protons.

This dissertation presents a search for the process $t \rightarrow q\gamma$ in the decay channel using top quark pair events. The process $t\bar{t} \rightarrow bWq\gamma \rightarrow bl\nu q\gamma$ will be searched for using the ATLAS detector. This final state ($bl\nu q\gamma$) is a straightforward channel in that it has one of each type of object that can be reconstructed with ATLAS. There are 2 jets from the quarks but one is a b-jet that has qualities that can distinguish it from a normal quark jet which will be discussed in Section 4.3.4.1. In addition to the

jets the final state also has a charged lepton (an electron or muon), a photon, and a neutrino. The reconstruction of these objects is discussed in Chapter IV. The FCNC process is a unique process where a top quark decays directly into an up-type quark and a photon. The jet and photon we measure are required to be reconstructed into a top quark by measuring the invariant mass requirement which gives an excellent handle for separating signal from background.

CHAPTER III

THE LARGE HADRON COLLIDER AND THE ATLAS DETECTOR

This chapter describes the experimental details of the collider complex at the LHC and specifically the ATLAS detector used to produce, collect, and measure various particle properties. The subsystems of the ATLAS detector are described in detail.

3.1. The Large Hadron Collider

The LHC is the world's largest and most energetic particle accelerator. As a hadron collider the LHC collides particles made up of quarks, typically proton-proton collisions. Protons, as opposed to electrons/positrons at a previous collider such as LEP, have much higher mass and a significantly smaller amount of energy loss during acceleration due to synchrotron radiation (which scales as $\frac{1}{m^4}$). Due to this the LHC is able to reach a much higher center of mass energy using the same circular ring used by LEP, though this higher energy comes at a cost. Due to hadrons being made up of constituent partons (quarks and gluons), not all of which interact in any given collision, the particles that do not take place in the hard interaction are left over and create a 'messier' environment in the detectors. This is opposed to lepton colliders, where all of the energy that goes into the collision is present in the final state particles coming from the interaction point. The implication of this is that at hadron colliders the momentum along the beam axis cannot be known, only momentum in the transverse plane of a collision is known due to conservation of momentum.

The LHC is housed in a 27 km ring running beneath the Franco-Swiss border near Geneva, Switzerland and accelerates beams of protons (ions) to a center of mass

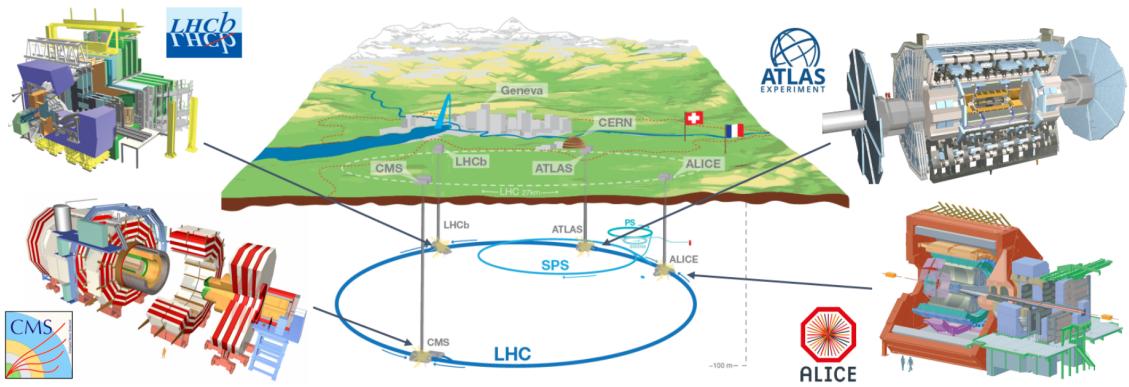


FIGURE 3.1. Map of LHC and the various detector experiments: ATLAS, CMS, LHCb, and ALICE located under the Franco-Swiss border near Geneva[34]

energy of 13 TeV (5 TeV) using two counterpropagating circular beams around the ring. The particles are then collided at one of the four primary interaction points, each of which house a dedicated detector as shown in Figure 3.1.

In addition to the LHC beam line the accelerator uses a series of smaller accelerators to increase the energy of the particles before being introduced into the LHC. This accelerator complex is detailed in Figure 3.2. The start of the accelerator chain, and source of LHC protons, is the Linear Accelerator 2 (LINAC 2, purple) where hydrogen gas is placed inside of an electric field that separates the protons and electrons. The remaining protons are passed through radiofrequency (RF) cavities and accelerated to 50 MeV using electric fields which oscillate at a frequency specific to the distance between any two RF cavities.

After leaving LINAC 2 the protons are injected into the Proton Synchrotron Booster (BOOSTER, light purple) and accelerated to 1.4 GeV before being passed to the Proton Synchrotron (PS, magenta) in two batches with a separation of 1.2 seconds. The PS accelerates the protons to 25 GeV to be injected into the Super Proton Synchrotron (SPS, blue) in a series of four batches separated by 3.6 seconds and are accelerated to 450 GeV. The SPS is the second largest accelerator in the

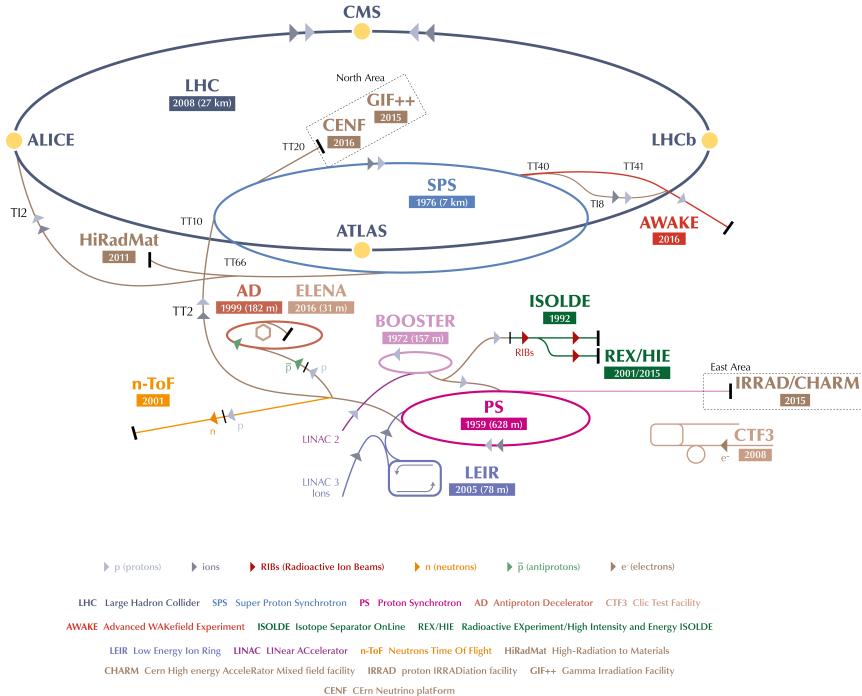


FIGURE 3.2. Schematic of the CERN accelerator complex.[35]

complex. After reaching the 450 GeV of the SPS the particles are split and injected into the LHC in opposing directions where they are further accelerated to a collision energy of 6.5 TeV per beam leading to a center of mass energy of 13 TeV for the LHC during Run-2.

The first proton-proton collisions were produced in the LHC in 2008 at the injection energy of the SPS, $\sqrt{s} = 900$ GeV. During testing a faulty electrical connection caused a magnet quench, or a sudden loss of superconductivity, to occur. This broke the nearby magnets and caused a delay in operations until late 2009 when LHC Run-1 began at a collision energy of $\sqrt{s} = 7$ TeV and later raised to $\sqrt{s} = 8$ TeV in 2012 to complete Run-1. Various upgrade and repairs on the LHC occurred

throughout the long shutdown between 2012-2015 where the center of mass energy was increased to the LHC Run-2 energy of $\sqrt{s} = 13$ TeV.

3.1.1. LHC Magnets

The energies achieved in the collisions are only possible due to the LHC magnets that bend and focus the colliding particles. The LHC uses the most powerful magnet technology that can be produced on an industrial scale. There are 1232 superconducting dipole magnets each being 15m in length, weighing over 35 tons, and producing uniform magnetic fields of up to 8.4 T. The niobium-titanium cables must be cooled to 1.9 K and operate with a current of 11,800 A. Of these 1232 magnets 1104 are used to bend the particles around the ring and the remaining 128 are used in the beam dump. To achieve the same center of mass energy using standard non-superconducting magnets the 27 km LHC would instead have to be upwards of 120 km long.

Since the bunches of particles are charged they will naturally diverge while traveling if not focused. To correct for this an additional 392 quadrupole magnets, 5-7m in length, are used to focus the beam. These quadrupoles are used in pairs: one which focuses in the horizontal plane and defocuses in the vertical plane and the other which focuses in the vertical plane and defocuses in the horizontal plane. Together these magnets keep the beam squeezed to a usable size. All of these magnets have two apertures, one for each of the counter-propagating beams.

3.1.2. Luminosity

The amount of data collected at collider experiments is determined not only by the center of mass energy of colliding particles but also the rate of events produced.

This rate is called the luminosity and can be determined by the square of the number of particles in each bunch (since any one in one bunch can interact with any one in the other), the time between bunches, and the cross section of the bunch (or probability of a collision).

$$\mathcal{L} = \frac{1}{\sigma} \frac{dN}{dt}$$

For any given proton-proton pair the luminosity can be expressed as:

$$\mathcal{L} = \frac{1}{4\pi\sigma_x\sigma_y}$$

and can be expanded for the whole beam with the inclusion of the number of protons per bunch (N_1 and N_2), the number of bunches (N_b), and the frequency at which the bunches overlap (f) to:

$$\mathcal{L} = \frac{N_1 N_2 N_b f}{4\pi\sigma_x\sigma_y}$$

which can be iterated over the running time of the LHC (the total time with beams of proper size and energy propagating through the LHC) giving the total delivered luminosity. This total integrated luminosity as a function of time during LHC Run-2 is shown in Figure 3.3. This luminosity value can be multiplied by the probability, or cross section, of any particular final state to obtain the number of times that final state is produced with a given luminosity.

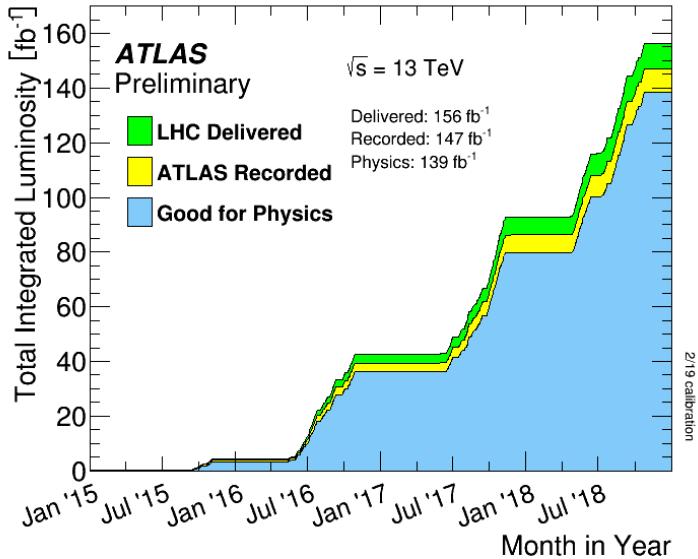


FIGURE 3.3. Total integrated luminosity as a function of time delivered by the LHC(green), recorded (yellow) and declared good for physics analysis (blue) by the ATLAS detector throughout Run 2 consisting entirely of 13 TeV pp collisions. [36]

3.1.3. Pileup

Increasing the luminosity is very beneficial for increasing the statistics needed when searching for rare events but it brings additional challenges as well. Most interactions at any given detector are not hard-scatter events that correspond to potentially interesting physics cases but are instead soft collisions which create noise in the various detector experiments. The LHC works hard to deliver as much data to the experiments as possible and delivers bunches of protons at a time. It is possible for multiple pairs of protons to undergo these soft inelastic collisions at a time. The average number of interactions per bunch crossing, or pileup $\langle \mu \rangle$, for Run-2 was 33.7, shown in Figure 3.4. The pileup must be accounted for when separating the tracks and energy deposited from an interesting hard-scatter event from the other soft collisions which occur at nearly the same time within a detector. The difficulty of separating out one event from another can be seen in Figure 3.5 where there are 28 reconstructed

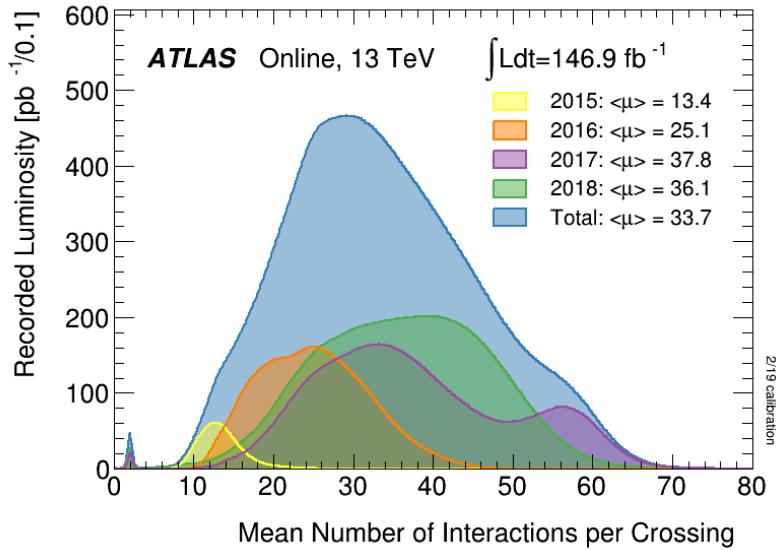


FIGURE 3.4. Luminosity-weighted distribution of the mean number of interactions per bunch crossing for the entirety of Run 2 shown by individual years, 2015 (yellow), 2016 (orange), 2017 (purple), 2018 (green), as well as an integrated total (blue).[36]

verticies. An extreme case of 65 reconstructed verticies is also shown in Figure 3.6. As the LHC will continue to operate at higher and higher luminosities in the future, the amount of pileup that will need to be dealt with will continue to increase.

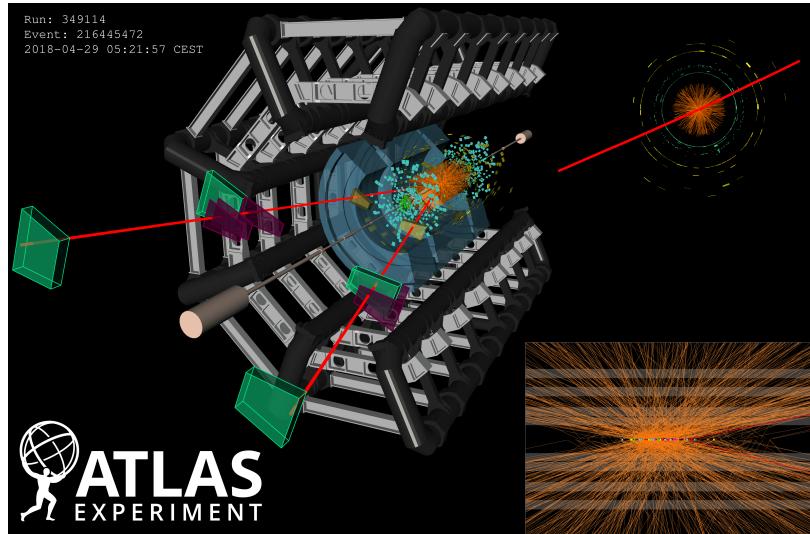


FIGURE 3.5. A candidate dimuon event ($Z \rightarrow \mu^+\mu^-$) with 28 reconstructed verticies collected in 2018 with the ATLAS detector.[36]

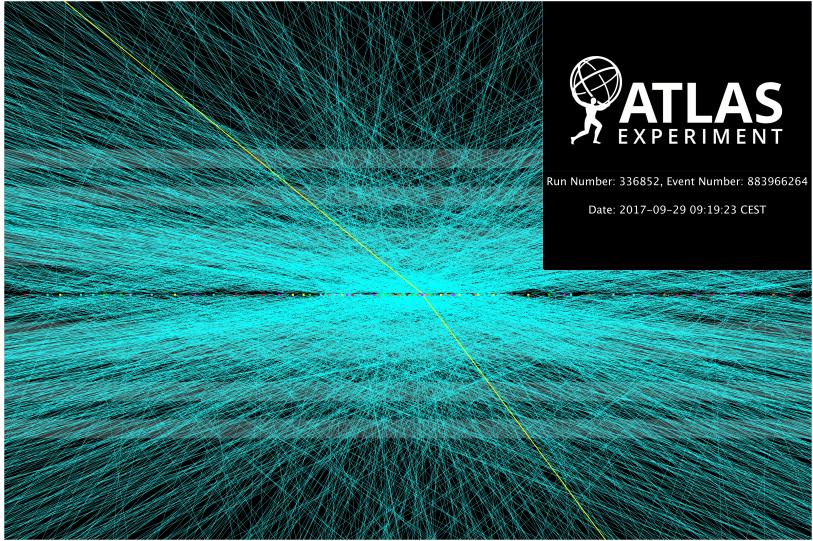


FIGURE 3.6. A candidate dimuon event ($Z \rightarrow \mu^+ \mu^-$) with 65 reconstructed verticies collected in 2017 with the ATLAS detector.[36]

3.2. The ATLAS Detector

The ATLAS detector, depicted in Figure 3.7, is one of the two general-purpose detectors at the LHC. It is the largest detector of its kind ever built at 46 meters in length, 25 meters in diameter, weighing 7000 tons, and containing around 3000 kilometers of cables[37]. Around the interaction points within the detector the ATLAS detector covers nearly the entire solid angle and is nominally symmetric. ATLAS is built up of a variety of concentric subsystems, which will be discussed throughout this section, each with a specialized task and optimized for the measurement of different particle signatures. The primary subsystems used to measure particle trajectories and momenta accurately are the inner detector (Section 3.2.3), the hadronic and electromagnetic calorimeters (Section 3.2.4), and the muon system (Section 3.2.5). The inner detector measures the paths of charged particles, called tracks. The electromagnetic and hadronic calorimeters measure the energy of charged and neutral

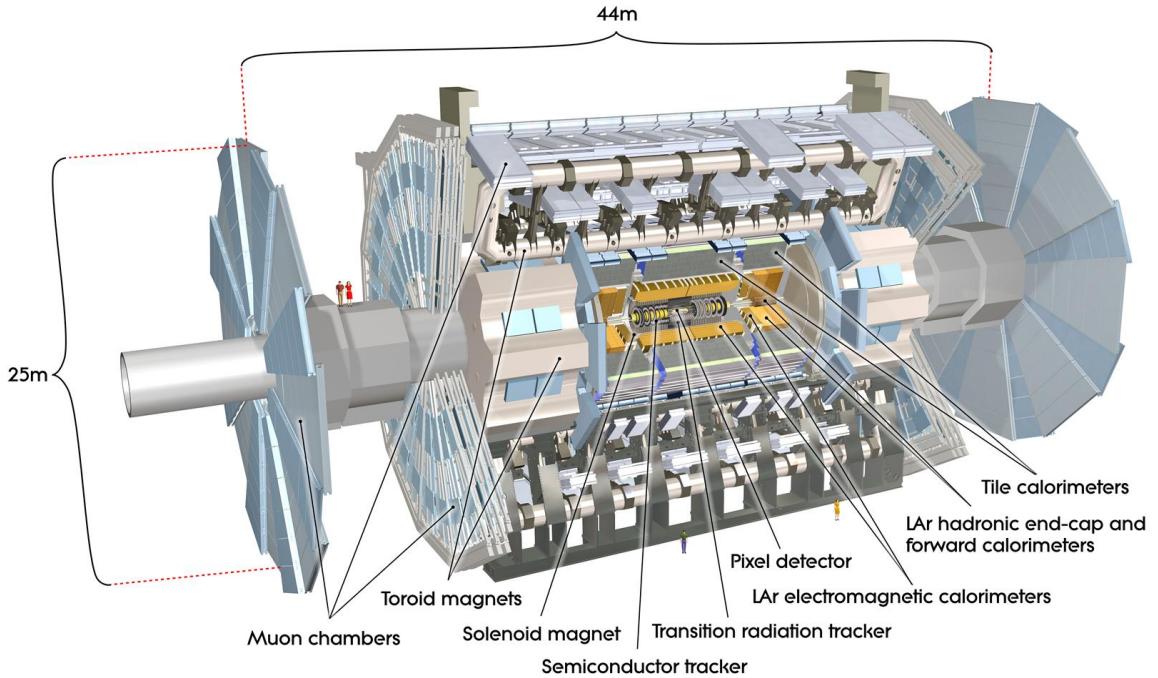


FIGURE 3.7. Schematic of the ATLAS detector.[37]

particles. The muon system measures the momenta of minimum ionizing particles (MIPs).

In addition to the various detectors and calorimeters the ATLAS detector has a magnet system (Section 3.2.2) that bends charged particles in the detector, allowing for a measurement of their charge and momentum and distinguishing them from neutral particles. Between the inner detector and the calorimeters is a solenoid which provides an axial magnetic field. Between the calorimeters and the muon system is a toroidal magnet, from which ATLAS got its original acronym (**A** Toroidal **L**H_C **A**pparatu**S**).

3.2.1. Common Detector Variables and the ATLAS Coordinate System

The ATLAS detector uses a right-handed coordinate system with the origin at the interaction point. In a Cartesian coordinate system the z-axis is defined to be along the beam pipe (positive towards LHC Point 8) while the x-axis points toward the center of the LHC ring which means the positive y-axis points upwards as shown in Figure 3.8. In practice coordinates used are a modified polar coordinate system. In the transverse (xy-)plane to the beam line the azimuthal angle, ϕ , is measured around the beam axis and radius, r , are used. Away from the transverse plane the pseudorapidity, η , is defined by the polar angle (from the y-axis), θ , to be $\eta = -\ln[\tan(\theta/2)]$. Differences in η are Lorentz invariant under longitudinal boosts such that the differences in the rest frames of colliding particles are not important for massless particles. Since the particles typically present in the ATLAS detector are highly energetic, and therefore have a large boost, the pseudorapidity is a good estimate of the true rapidity of the particles. Massless particles are also produced uniformly in η and not in θ which is why η is preferred.

The distance between any two objects within the ATLAS detector can be described geometrically by the variable $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Another common variable used is the missing transverse energy, E_T^{miss} . The information known about the missing energy is limited to the transverse plane because the momenta of the colliding particles is unknown along the beamline.

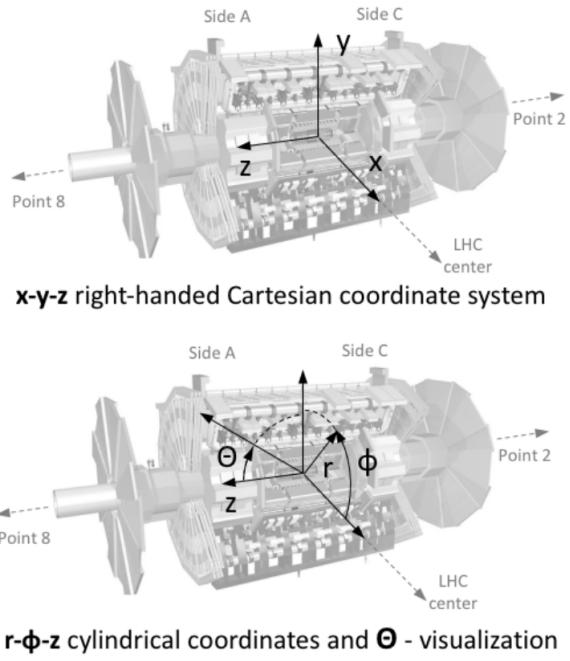


FIGURE 3.8. Coordinate system used in the ATLAS Collaboration.[34]

3.2.2. Magnet Setup

The ATLAS detector has two magnet systems of note. The first is the superconducting solenoid that surrounds the inner detector with a magnetic field aligned with the beam axis. The solenoid has a magnetic field of 2T that makes the tracking of charged particles possible with the inner detector. This magnet is a thin single layer coil, which is imperative to minimize the amount of material in front of the calorimeters.

The toroid system consist of two parts, the end-cap and the barrel magnets. The windings of these magnets is shown in Figure 3.9. Each of these magnets consists of eight superconducting air-core coils, together weighing 830 tons. The end-cap coils are interleaved with the barrel coils. A peak magnetic field strength of 3.9T (4.1T) is achieved in the barrel (end-cap) toroid which assists in the track and momentum

measurement of high energy muons as they leave the ATLAS detector. The barrel toroids cover a range of $|\eta| < 1.4$ while the endcap toroids cover the range $1.6 < |\eta| < 2.7$. The remaining region is covered by a combination of the field of the two sets of toroids.

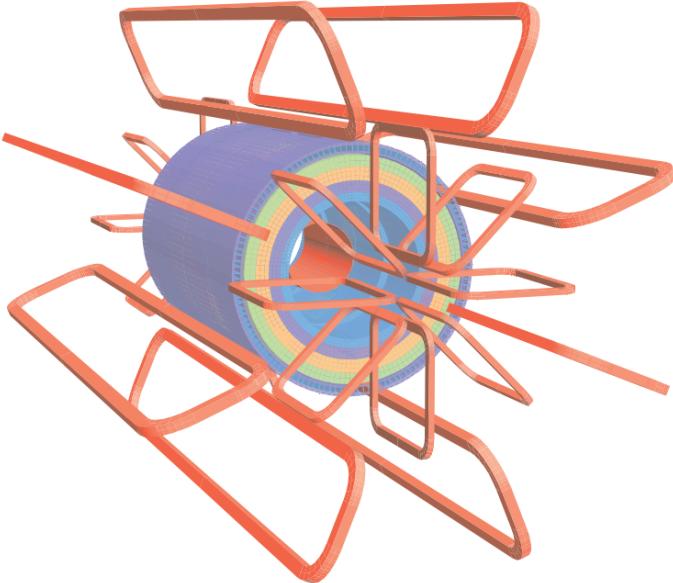


FIGURE 3.9. Schematic of the windings of the ATLAS magnet.[37]

3.2.3. Inner Detector

The inner detector sits inside the solenoid magnet and is used to reconstruct charged particle tracks as they bend due to the magnetic field. The inner detector is made up of four distinct parts. The Insertable B-Layer (IBL) [38], the Pixel Detectors, the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT)[39]. The inner detector provides complete coverage for charged particle tracking, extending to $|\eta| < 2.5$. Momentum resolution as well as primary and secondary vertex measurements are done using the inner detector. Secondary vertices are important for identifying of particles with delayed decays such as bottom quarks (Section 4.3.4.1),

charm quarks, and tau leptons. A schematic of the inner detector can be seen in Figure 3.12.

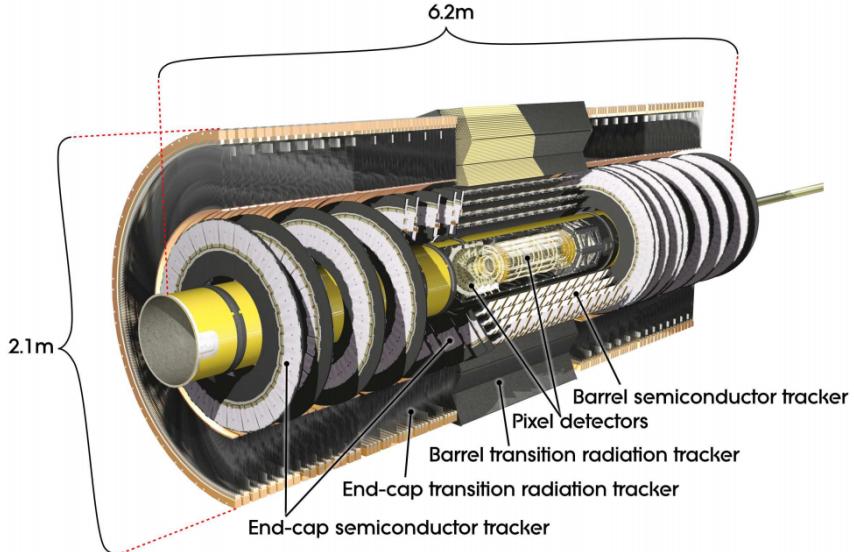


FIGURE 3.10. Schematic of the ATLAS inner detector.[37]

The IBL was added during Long Shutdown I (2016) of the LHC and is closer to the interaction point than the innermost layer in Run 1. This required adding a smaller beam pipe (reduction in radius from 29 mm to 25mm) but was able to improve the resolution of vertexes and thus the reconstruction of events involving bottom quark decays as well as allowing for charm quark decays to be classified better than ever before. This improvement is shown in Figure 3.11 in a study of the impact parameter resolution. An improvement of up to 40% is seen with the inclusion of the IBL in the low p_T region. The IBL functions as a fourth layer of the Pixel Detector and uses planar sensors (similar to the Pixel Detector) as well as 3D sensors allowing electrons to interact with the bulk of the sensor as opposed to just the surface.

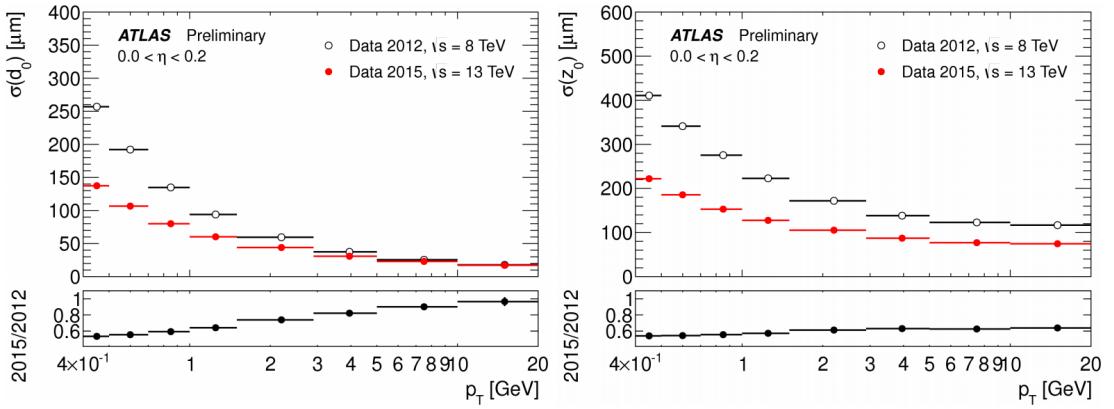


FIGURE 3.11. Unfolded transverse (left) and longitudinal (right) impact parameter resolution measured with (Run 2) and without (Run 1) the IBL as a function of p_T .[40]

The next layer from the beam pipe, as detailed in Figure 3.12, is the Pixel Detector which is a series of high granularity silicon pixel detectors which measure a position when a charged particle passes through them. These silicon pixels are n-doped silicon wafers biased with a high voltage that allow for the creation of electron hole pairs. The electron then drifts toward the electrode which creates the position signal in the readout electronics. In addition to the IBL there are three more cylindrical layers which are designed to ensure single pixel isolation and minimize leakage. The pixels are $50 \times 400 \mu\text{m}^2$. For complete coverage to the cylindrical system, endcaps are placed on each side of the central barrel. These endcaps consist of four wheels that have trapezoid shaped silicon pixels. The three barrel layers consist of 67 million pixels and the endcaps total an additional 13 million pixels. After the Pixel Detector is the Semiconductor Tracker (SCT) which is also made up of barrel and endcap detectors. The barrel SCT is four cylindrical layers of silicon microstrip trackers where the endcaps are nine discs on each side of the barrel made up of either silicon or gallium arsenide semiconductors. The SCT contains over 60m^2 of silicon detectors with over 6 million readout channels.

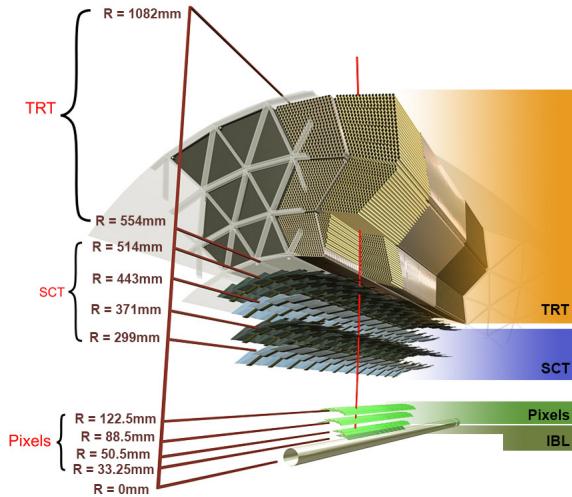


FIGURE 3.12. Blown up schematic of the ATLAS inner detector with more detail.[41]

The final part of the Inner Detector is the Transition Radiation Tracker (TRT) [42]. The TRT is a straw detector surrounding the SCT. Every straw is a 4 mm in diameter Kapton tube with a 0.03 mm diameter gold-plated tungsten wire in its center. In the barrel region there are 50,000 straws that are each 144 cm long and an additional 250,000 straws in both endcaps which are 39 cm in length. Each straw is filled with an active gas mixture made up of mostly Xenon or Argon.

When charged particles traverse across the TRT straws they ionize the active gas mixture and produce ionization clusters. The amount of clusters created depends on how far the charged particle traveled through the TRT (5-6 clusters per mm). The straw walls are held at a high negative voltage such that the primary electrons are accelerated toward the gold-plated tungsten wire anode creating more ionization by liberating more electrons from the active gas and producing a detectable signal which is amplified and read out. Transition radiation occurs when a particle makes a transition between materials with different dielectric constants and the energy radiated is directly proportional to the Lorentz factor of the particle. This allows for an excellent discrimination between electrons and charged pions.

3.2.4. Electromagnetic and Hadronic Calorimeters

While the inner detector focuses on tracking the charged particles as they pass through the detector the ATLAS Calorimeter system is designed to absorb and measure the energy of neutral and charged particles. The exceptions to this are muons which are able to penetrate through the calorimeters into the muon and neutrinos which do not interact at all within the ATLAS detector. The calorimeters can be broken down into two major systems, the Liquid Argon (LAr) calorimeter[43] and the tile calorimeter (TileCal)[44]. Both of these systems are shown in Figure 3.13.

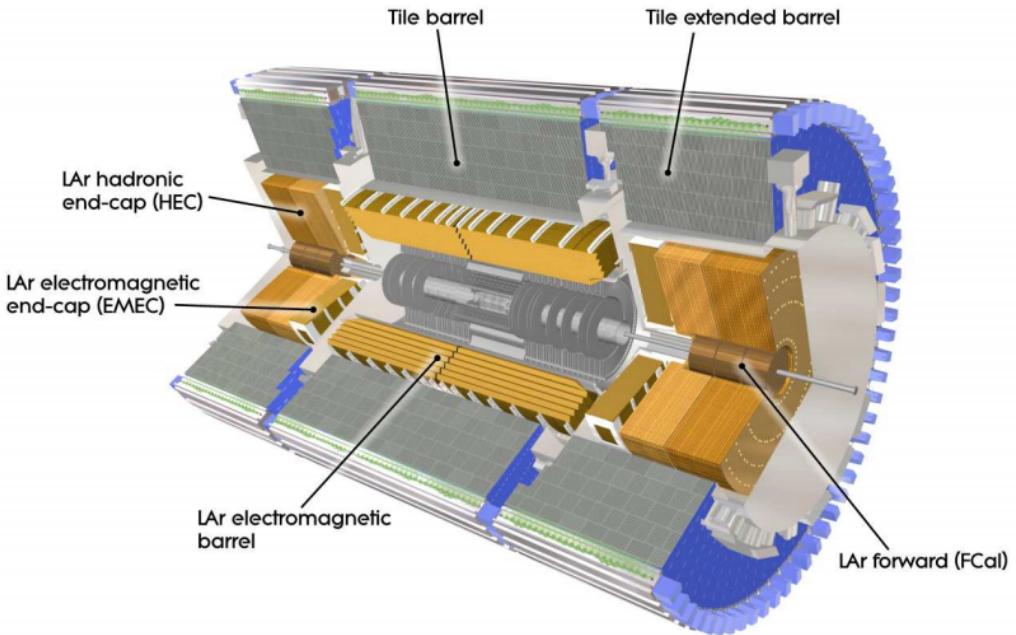


FIGURE 3.13. Schematic of the ATLAS hadronic and electromagnetic calorimeter systems.[37]

The LAr calorimeter is a sampling calorimeter. Sampling calorimeters use alternating layers of a dense absorbing material and an active material to measure the signal produced by showering particles. The LAr calorimeter uses lead as the absorbing material and liquid argon measured with copper-tungsten sensors as the

active layer. The layers in the LAr calorimeter are arranged in an "accordian-shaped" geometry shown in Figure 3.14 to provide complete azimuthal coverage. This allows for the electromagnetic energy resolution to be uniform in the azimuthal direction. Sampling calorimeters do not directly measure the entire energy of the particle, only the interactions that occur in the active layers. The stochastic nature of the processes being measured means that large fluctuations can occur while measuring electromagnetic showers. These fluctuations mean that sampling calorimeters must account for sampling statistics as opposed to other types of calorimeters where the entirety of the energy is absorbed with an active layer, such as scintillators.

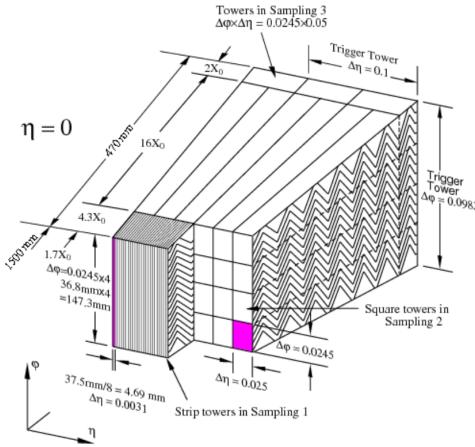


FIGURE 3.14. Sketch of the accordian structure used in the LAr Calorimeter.[43]

For sampling calorimeters it is important to know the ratio $\frac{E_{\text{visible}}}{E_{\text{deposited}}}$ so that the energy of a particle can be reconstructed based on only the energy measured by the active layers. This ratio must be measured with test beams where the original beam energy is known precisely. Sampling calorimeters allow for the complete detection of electromagnetic showers. Because there is a large amount of material to traverse through, all of the energy can be deposited within the detector. The amount of material traversed by each particle is an important aspect as it includes not only the

active material and absorber but also the support structures and cables that can play a role in particle interactions. The thickness of a material passed through is typically measured in radiation lengths (X_0), where an electron passing through one radiation length will lose $1/e$ of its energy to bremsstrahlung. The amount of radiation lengths in the LAr calorimeter is shown in Figure 3.15.

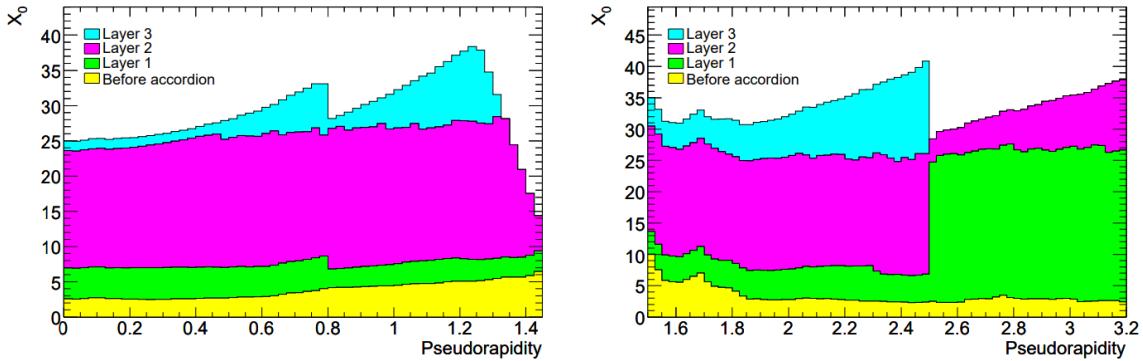


FIGURE 3.15. Number of radiation lengths throughout the LAr calorimeter as a function of $|\eta|$ [37]

Forward from the barrel there are two electromagnetic endcap (EMEC) wheels with a similar accordion structure to the modules in the barrel that cover ranges $1.4 < |\eta| < 2.5$ and $2.5 < |\eta| < 3.2$. Outside of the EMEC wheels is the LAr hadronic endcap (HEC) with a simpler parallel plate structure. The last part of the LAr calorimeter is the LAr forward calorimeter (FCal). Due to the FCal's proximity to the beamline the particle flux is very high so a dense calorimeter is used to avoid losing energy into other pieces of the detector. The FCal is made up of three layers: the first is copper and the others are tungsten.

The remaining calorimeter system is the TileCal which is primarily responsible for hadronic calorimetry in the central region $|\eta| < 1.7$. TileCal is also a sampling calorimeter with iron plate absorbers and plastic scintillating tiles. The scintillating tiles are placed orthogonal to the beamline and readout using wavelength shifting

fibers connected to photomultiplier tubes on the outside of the system. TileCal has a fixed central barrel and two extended barrel sections as shown in Figure 3.13. The extended barrel sections can be moved. The total nuclear interaction length of the TileCal is 7.4λ , where λ is the mean distance a hadronic particle will travel before experiencing an inelastic interaction with the material it is traveling through. The total interaction length for each section of the calorimeter is shown in Figure 3.16.

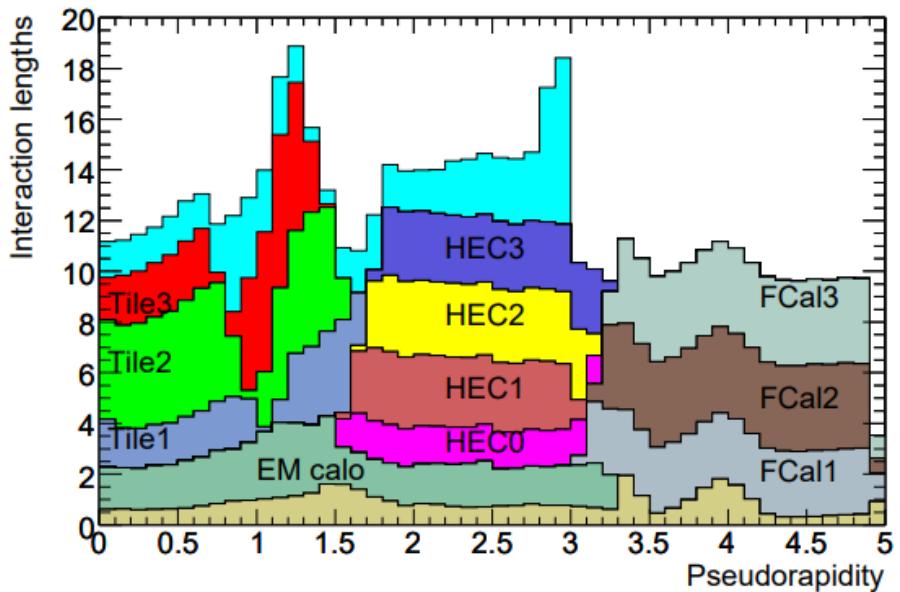


FIGURE 3.16. Number of radiation lengths throughout the LAr calorimeter as a function of $|\eta|$ [37]

3.2.5. Muon System

The final and outermost subdetector of the ATLAS detector is the muon spectrometer, which measures the momentum of muons. Different technologies are used in the barrel and endcap regions for both measurement and triggering (deciding which events to keep when only a small fraction of events can be recorded). For the barrel region, $|\eta| < 2.7$, three layers of Monitored Drift Tubes (MDT) are used for

precision energy and tracking measurements and Resistive Plate Chambers (RPC) for triggering. In the forward region, $2.0 < |\eta| < 2.7$, where the flux is higher, Cathode Strip Chambers (CSC) are used for energy and position measurements, and Thin Gap Chambers (TGC) are used for triggering. These systems, shown in Figure 3.17, are aided by the magnetic field created by the toroid system discussed in Section 3.2.2.

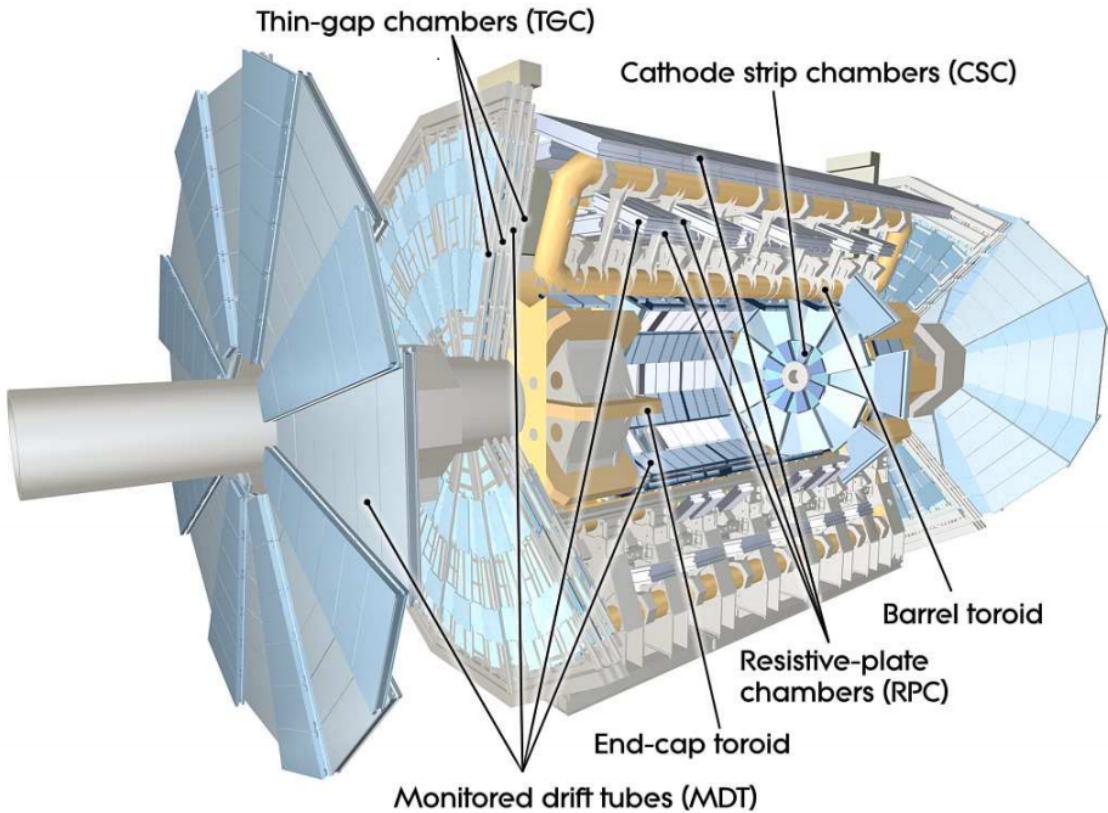


FIGURE 3.17. Schematic of the ATLAS muon detector.[37]

MDTs are arranged in chambers of up to 6 layers of aluminum tubes ranging in length from one to six meters. Each tube is 30 mm in diameter and contains a sense wire 50 μm in diameter. The chambers are arranged with a support spacer in between layers of MDTs that have a built-in optical sensor to monitor the drift tubes (hence the name) for deformations. This ensures that the precision of measurements does

not change over time. The MDTs are only used in the barrel and not in the forward region because they are inappropriate in areas with high rates, in this case a high flux of muons.

For the forward region CSCs are used. CSCs consist of arrays of positively charged wires crossed with negatively charged strips within a gas. As muons pass through they knock electrons from atoms in the gas which go toward the anode wires. Since the strips and wires are perpendicular to each other two position coordinates are read out. CSCs have the benefit of giving acceptable one and two-track resolution in a high flux environment.

The trigger system for muons in the barrel region uses RPCs which are parallel plates with opposite charges separated by a gaseous volume. A muon passing through an RPC knocks electrons from the gas which cause an avalanche of electrons that get picked up by the external metal strips rather than by the electrode. The pattern of metal strips that gets hit gives a quick measurement of the muon momentum which is used by the trigger to make the immediate decision about the event. The endcap muon trigger relies on TGCs. TGCs are anode wires with graphite cathodes in between thin layers of fiberglass laminate. Similarly to why CSCs are used over MDRs in the forward region TGCs have excellent timing resolution and can handle the high flux of muons in the forward regions.

3.2.6. Trigger and Data Acquisition

The amount of data the LHC is capable of producing is staggering, and the ATLAS trigger system is required to reduce the enormous amount of data produced to a reasonable amount while keeping the most interesting events. The LHC provides collisions at a rate of 40MHz. Every event saved to tape requires about 1.6MB of

space [45]. To keep all of the data produced 64TB/s would need to be saved or 230PB of data for a 12-hour run or 400EB of data per year (150 days of uptime).

In order to reduce this to a manageable level the ATLAS trigger system uses a two level trigger system. A hardware trigger, Level 1 or L1 trigger, is used to lower the rate from 40MHz to between 75 and 100kHz which is sent to the next level of the trigger system, the High Level Trigger (HLT). Another factor of 50 in rate reduction is achieved by this software based HLT to reduce the rate below 2kHz. A flowchart of the ATLAS trigger and data acquisition system is shown in Figure 3.18. When combined with partial event readouts and the <2kHz full event readout the total bandwidth requirement is around 3GB/s to be written. This means that only around 0.004% of data is stored.

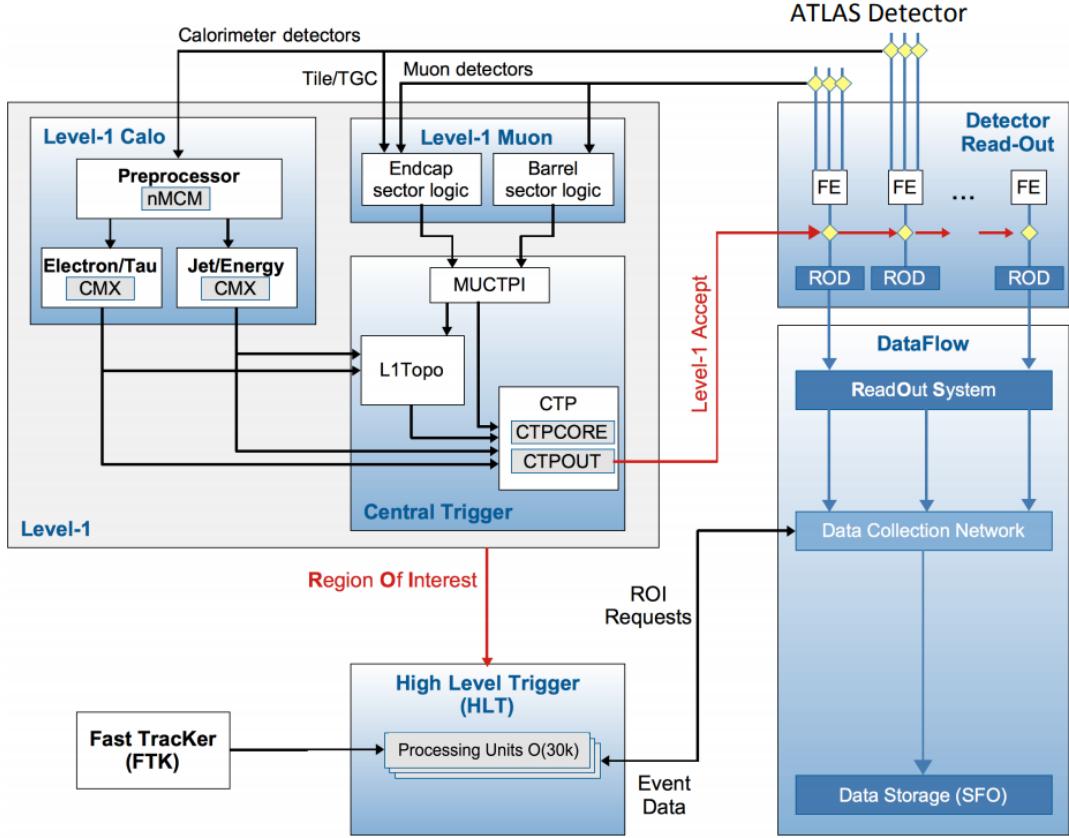


FIGURE 3.18. Flow diagram of the ATLAS trigger and data acquisition system used in Run 2.[46]

3.2.6.1. Level 1 Calorimeter

The Level 1 hardware trigger uses geometrically coarse information from some of the subdetectors. The data from the calorimeters is sent to the Level 1 Calorimeter (L1 Calo) system. L1 Calo uses low granularity information to identify Regions of Interest (RoIs) from objects that interact in the calorimeters (e.g., photons, electrons, jets, taus), events with high total energy, as well as events with an imbalance of energy coming from missing transverse energy. The information is fed into the L1 Calo system and through a preprocessor that allows L1 Calo to handle the effects within ATLAS from pileup events. Data from TileCal and the trigger portions of the muon systems

goes to the Level 1 Muon (L1 Muon) system which applies various logical processes to determine whether or not an event should be kept. Outputs from L1 Calo and L1 Muon are passed to the Central Trigger Processor (CTP) which provides a level 1 trigger accept and LHC timing information to the detector read out. At the same time the CTP gives RoIs to the HLT.

3.2.6.2. High Level Trigger

The HLT takes RoIs from the CTP as well as full detector granularity and makes a further decision whether that event should be saved. This is done using a computing farm of over 40,000 cores that run over 2,500 independent algorithms (trigger chains) on the RoIs. The HLT can provide partial and full event reconstruction depending on the event stream the event is decided to be within. The main event stream is the physics analysis stream which gets full event reconstruction, while the other streams typically only require partial event reconstruction. The other streams are used for a variety of things such as trigger level analysis, monitoring of the subsystems, and calibrating the detector.

CHAPTER IV

SIMULATION AND RECONSTRUCTION

This chapter presents details on the simulation of various physics processes and the reconstruction of physics objects for both simulated events and data events.

4.1. Simulation of pp Collisions

To draw conclusions from ATLAS experimental data it is necessary to make accurate theoretical predictions about the processes being searched for. Having accurate background models can help identify when a data signal is behaving in a way that might suggest new physics. Due to the stochastic nature of particle physics collisions and interactions it is not practical to create exact predictions, instead the ATLAS experiment uses Monte Carlo (MC) simulations to make predictions. MC simulations are done by repeated random sampling of possible physical processes that can occur at any given time to a particle. The possibilities change based on factors such as particle energy and particle environment. A flow chart for the entire simulation chain is shown in Figure 4.1.

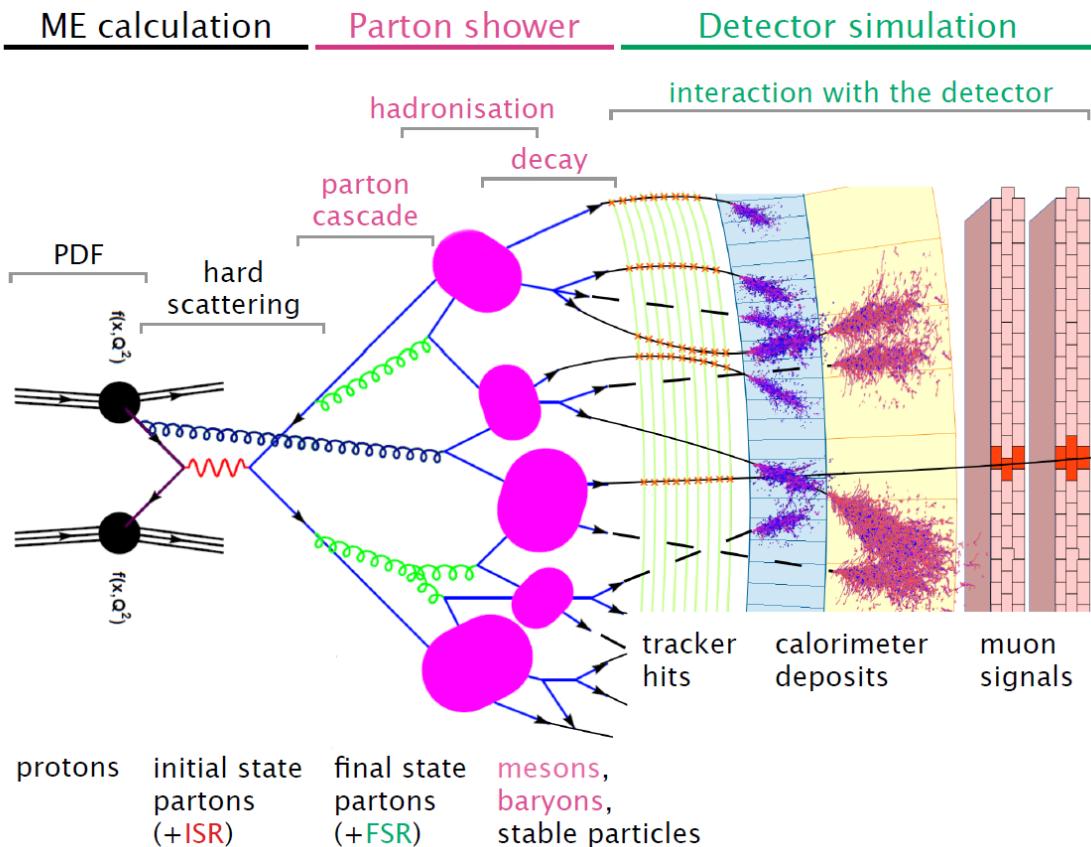


FIGURE 4.1. A pictoral view of the different steps for the creation of a MC event. [47]

4.1.1. Matrix Element Calculation and Parton Distribution Functions

Particle interactions at LHC energies do not involve the entire proton. The constituent partons that create the proton (the two up quarks, down quark, and the sea of gluons) are what interact in any given event. The gluons create many virtual quark-antiquark pairs which can interact as well. The valence quarks, the ups and down that make up the proton, are the major portion of interacting partons at low energies, mainly inelastic interactions. At LHC energies deep inelastic scattering is possible and the sea quarks play a more dominant role. Proton structure is described

by a Parton Distribution Function (PDF) which gives the probability of finding any parton with a particular momentum fraction and is shown in Figure 4.2.

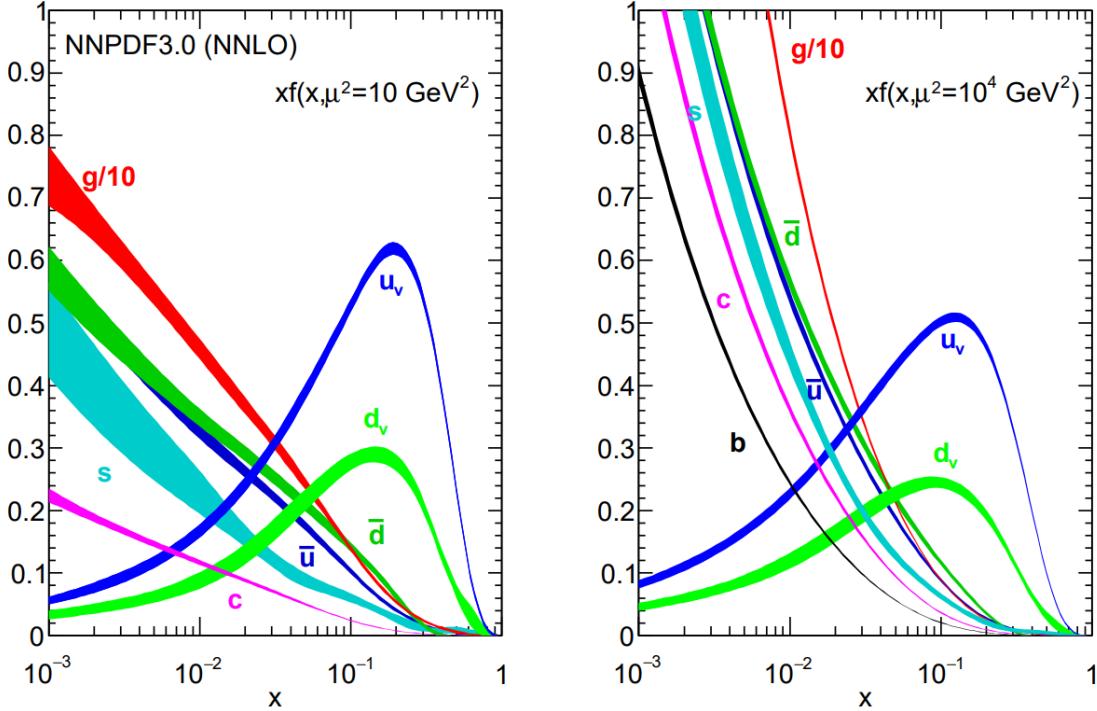


FIGURE 4.2. The bands are the momentum fraction, x , times the unpolarized parton distribution function obtained in NNLO NNPDF3.0 global analysis at scales $\mu^2 = 10 \text{ GeV}^2$ and $\mu^2 = 100 \text{ GeV}^2$ [10]

The PDFs and hard scattering processes are included in the calculation of the Matrix Elements (ME) of any interaction. Hard scattering processes can be described by Feynman diagrams, a representation of their amplitudes. Combining the PDFs and hard scattering amplitudes gives the probability of a particular interaction occurring. Calculation of the MEs is the first stage of simulation and is done to a specified order in perturbation theory: leading order (LO), next-to-leading order (NLO), etc. Higher order calculations lead to more accurate predictions but grow in complexity exponentially making them hard to calculate both theoretically and computationally. This is what often restricts how accurate a process can be simulated.

4.1.2. Parton Shower Calculation

The next stage of simulating an event is the parton shower. These parton shower calculations deal with the quantum chromodynamic processes. In any interaction the particles that carry color can spontaneously emit gluons which can go on to create more gluons or quark-antiquark pairs. Depending on when this happens in the hard scattering process it is called initial state radiation (ISR) or final state radiation (FSR). The hard scattering partons as well as any additional radiated particles are used as inputs to parton shower calculations which determine how the quarks and gluons proceed through to the final state particles seen in the detector. This includes calculation of hadronization processes and further decay processes into the final state particles.

4.1.3. Detector Simulation

The final stage of creating a MC event is the detector simulation. The information from the event generators are processed using GEANT4 [48] and a detailed model of the ATLAS detector. GEANT4 simulates how various particles propagate through and interact with the material properties of the detector and where they leave energy which would then be measured by the ATLAS detector in an actual event. The result of this MC event construction flow is a collection of simulated data that is similar in structure to actual data collected using the ATLAS experiment. The energy deposits in both MC and real data are then reconstructed using the same software and physics objects are reconstructed. For MC this allows for comparison between the physics object reconstruction and the truth record, or the types of particles fed into the detector simulation.

4.1.4. Monte Carlo Generators Used for LHC Physics

A variety of different MC generators are used in the creation of simulated events. Different generators can specialize in simulating different physics processes and handle various precision (eg., LO vs. NLO). The MC generators used in this search are summarized in this section.

MADGRAPH aMC@NLO [49]: An amplitude and event generator at LO and NLO for hard processes. Extendable to various models including effective field theory (EFT) models used in BSM searches. This generator is used to create the signal events searched for in this dissertation: discussed in Section 4.2.

POWHEG [50, 51]: **P**ositive **W**eight **H**ardest **E**mission **G**enerator is an NLO event generator that can be interfaced with other generators (i.e. PYTHIA) for showering.

PYTHIA [52]: A generator used most often for QCD final state hard processes and showering. It is commonly interfaced with other generators for showering within the ATLAS detector. **SHERPA** [53, 54]: A multi-parton LO generator with an emphasis on merging ME and Parton Showering.

These generators are commonly interfaced, usually with PYTHIA for showering, and this is possible due to a common file format developed at the Les Houches Accords [55]. This allows a specialty generator to be created and used to generate hard processes and then simulate the rest of the event with common showering generators that might lack the ability to simulate the process in question.

4.2. Creation of Flavor Changing Neutral Current Signal Events

To create simulated signal events the typical Standard Model models must be extended to include higher order terms. A Universal FeynRules Output (UFO, [56]) model was created to include dimension 6 operators ([57, 58]). These individual

operators are turned on for the specific final state being produced. The original operators can be reduced to a minimal set of coupling to anomalous final states (i.e. FCNC final states) [59] which are used. This effective field theory method of signal production is beneficial as it allows for production of signal events that are not dependent on any particular BSM model. This method of including dimension-6 effective operators can be used to produce any of the top FCNC channels, for example in the $t \rightarrow qZ$ process [60] and $t \rightarrow qH$ [61].

4.2.1. FCNC Events Produced With MadGraph5 amc@NLO

Signal events have been produced using MadGraph5 amc@NLO following [62]. Before official ATLAS datasets can be produced and the entirety of the event reconstructed through the entire ATLAS detector validation of the model must be performed. 10,000 events were produced locally at truth level to compare the kinematics of produced events in $t\bar{t} \rightarrow bWq\gamma$ to the kinematics of official production $t\bar{t}$ events.

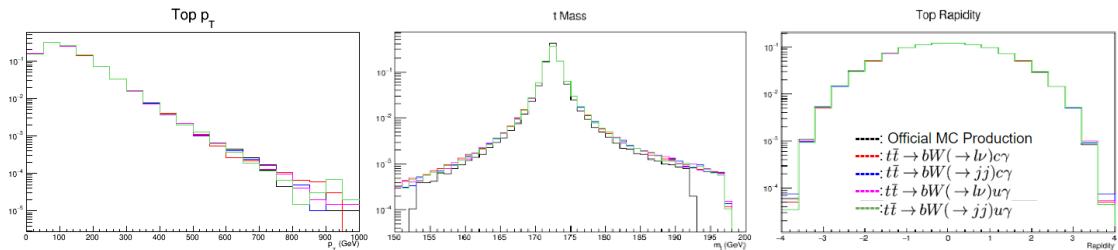


FIGURE 4.3. Normalized kinematics (p_T , m_t , and y_t) of individual top quarks produced by the model for each FCNC final state search and an official $t\bar{t}$ sample.

The minimal couplings mean there is one scalar coupling introduced for each decay mode, $t \rightarrow c\gamma$ and $t \rightarrow u\gamma$. All possible final states are shown in the figures in this section, the leptonic and hadronic decays of the W boson from the top quark that decays through the typical standard model decay mode $t \rightarrow bW$.

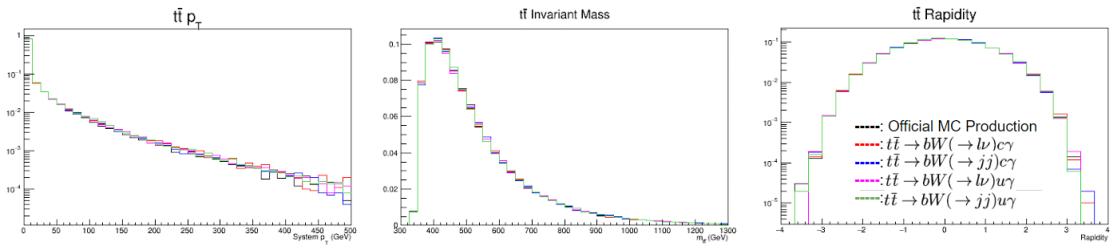


FIGURE 4.4. Normalized kinematics (p_T , $m_{t\bar{t}}$, and $y_{t\bar{t}}$) of the $t\bar{t}$ system produced by the model for each FCNC final state search and an official $t\bar{t}$ sample.

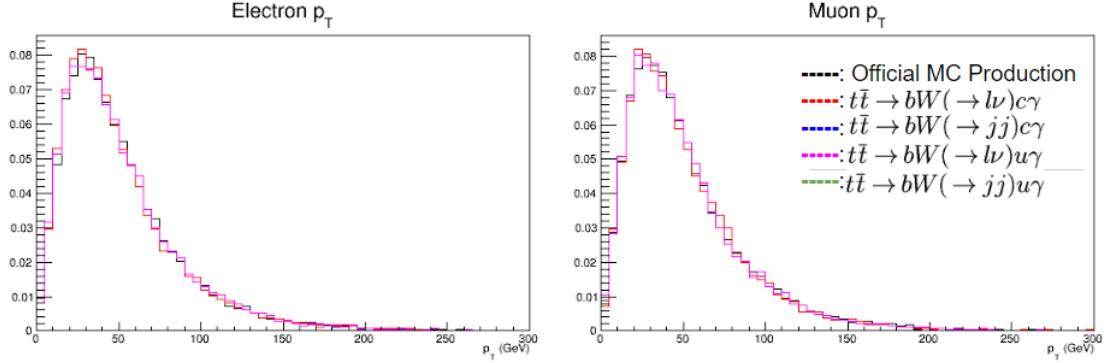


FIGURE 4.5. Normalized p_T of the electron and muons produced by the model for each FCNC final state search and an official $t\bar{t}$ sample.

The lepton validation plots, Figure 4.5 only show events where the W is forced to decay leptonically, as expected as well as the official sample which does not have a preference for the final state decay, the W bosons are allowed to decay leptonically or hadronically. No unexpected deviations from the Standard model produced $t\bar{t}$

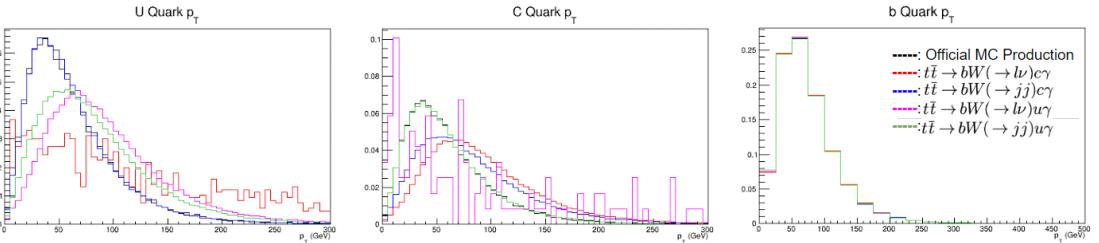


FIGURE 4.6. Normalized p_T of the up, charm, and bottom quarks produced by the model for each FCNC final state search and an official $t\bar{t}$ sample.

samples are seen in any of the validation plots. The deviations seen in Figure 4.6

are misplaced quarks from NLO processes. The shifted values in the up and charm p_T spectrum are also expected as those samples the up or charm is coming directly from the top quark as opposed to a W boson which means it will have significantly boosted momentum.

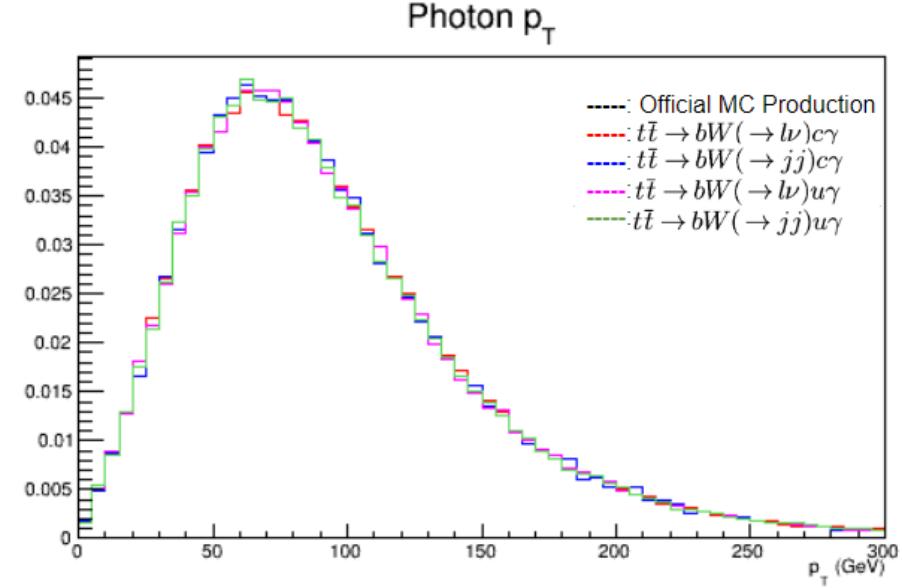


FIGURE 4.7. Normalized p_T of the photons produced by the model for each FCNC final state search and an official $t\bar{t}$ sample, there is 0 contribution from the official $t\bar{t}$ sample.

In the model there are left and right handed scalar couplings. Investigation into differences between the kinematics of the quarks produced using each of these couplings is shown in Figure 4.8.

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

No differences in final state kinematics were shown in the right-handed coupling compared to the left-handed coupling. Due to this only one coupling value was used in the production. In the end only leptonic decays of the W were produced officially. The

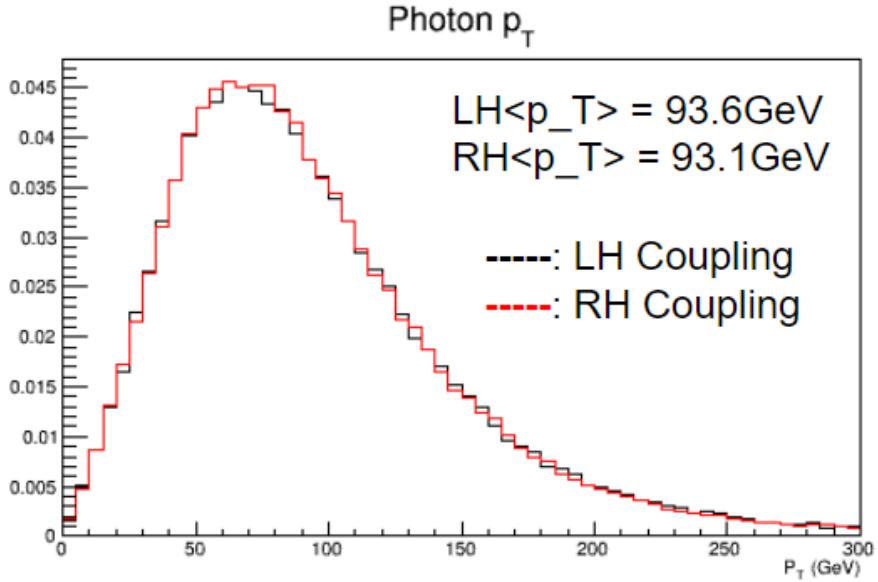


FIGURE 4.8. Normalized p_T of the photons produced by the model using the Left-handed (LH) and Right-handed (RH) couplings

leptonic state is simpler to search for than a final state not involving leptons because of the much larger backgrounds from QCD processes. The lepton offers many handles for searching for these rare FCNC days. Using the leptonic final state one does not have to use combinatorics for event reconstruction as each object is unique and comes from one particular object. In this analysis the final state involves a light jet and a photon (from the FCNC decay) and a lepton, photon, and b-jet (from the Standard Model top decay).

4.3. Object Reconstruction

After the events are simulated, or collected in case of real data, all there is is a collection of energy deposits within the detector. These energy deposits must be transformed into meaningful physics objects through reconstruction. Reconstruction is typically done in two major parts using the specialized detectors covered in Chapter

III. The Inner Detector and Muon System turn patterns of hits within the tracking detectors into tracks that have direction and momentum information. The calorimeter system transforms the energy deposits within the calorimeters into calibrated energy deposits with a particular position. These tracks and calorimeter deposits are used to create physics objects (electrons, muons, etc.) by using particle identification techniques to reconstruct the underlying physics event. For the analysis presented in this dissertation the final state signal particles that need to be reconstructed are one lepton (an electron or a muon), one photon, two quarks (one light flavor and one b quark), and one neutrino (missing transverse energy as it is the only particle that does not interact with the detector). Each of these particles has a particular signature in the subdetectors of the ATLAS detector, shown in Figure 4.9.

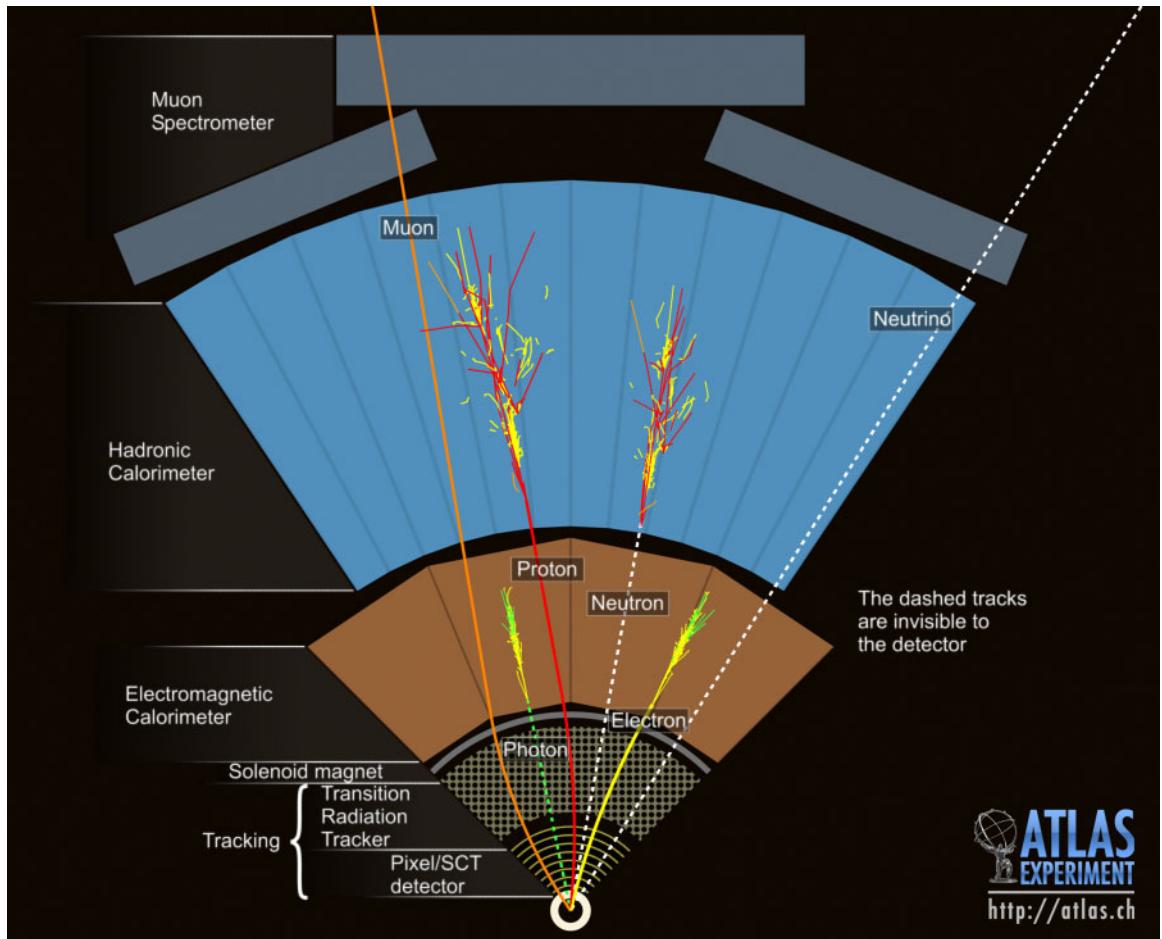


FIGURE 4.9. Cross section of a simulated ATLAS detector showing how various particles interact with ATLAS subsystems. Solid lines indicate interactions while dashed lines indicate that no interactions typically occur in that section of the detector. [63]

4.3.1. Electrons

Electrons interacting with the ATLAS detector leave a track in the Inner Detector as well as a cluster of energy in the electromagnetic calorimeter. The track and cluster are required to be matched together to be identified as an electron candidate[64]. As electrons move through the detector they create electromagnetic showers through bremsstrahlung which can produce electron-positron pairs. The process continues as

the particles continue to give energy to the detector. This collection of electrons, positrons, and photons creates a signature energy cluster in the calorimeter.

Electron identification algorithms are applied to the electron candidates to separate prompt and isolated electron candidates from electrons that come from backgrounds such as converted photons and misidentified jets. The electron identification algorithms use a sliding window (3×5 in $\eta \times \phi$) in the high granularity section of the LAr electromagnetic calorimeter to search for electron cluster “seeds” greater than 2.5 GeV. Clusters are created around these seeds to form the electromagnetic shower and remove possible duplicate electron signals by containing them within the cluster. Further pattern recognition for the track fitting allows even larger amounts of energy into the shower to account for bremsstrahlung in the shower shape. Tracks and clusters are then matched to give electron candidates.

Electrons coming from background jets or photon conversion are called non-prompt as they do not originate from a signal object. In order to reject these electrons other discriminating variables are used in addition to the track-cluster matching. Variables such as the energy leakage into the hadronic calorimeter, how the shower developed throughout the electromagnetic calorimeter, and the amount of radiation measured in the TRT. Three electron identification working points are used: Loose, Medium, and Tight. Each of these operating points have their own level of background rejection and signal efficiency. Working points with higher background rejection are a subset of those with lower background rejection.

Isolation variables are another useful tool in the identification of signal electrons from converted photons produced in hadron decays and light hadron misidentification. These variables are defined by a cone size around the electron candidate and are the sum of the transverse variable (momentum or energy) of all of the tracks within the

cone, $p_T^{\text{varcone}0.2}$ with a cone of $\Delta R = 0.2$ (or $10 \text{ GeV}/E_T$, for high energy electrons) and $E_{T,\text{Topo}}^{\text{varcone}0.4}$ with a cone defined in a similar manner.

Since the LAr calorimeter is a sampling calorimeter the energy deposits must be calibrated and scaled such that the true electron energy is read out not just the small amount of energy deposited into the active layers as discussed in Section 3.2.4. The energy scale is calibrated to be uniform throughout the detector. Any residual differences between data and simulation are corrected. The calibration strategy was developed for optimal performance in LHC Run 1[65] and updated for the conditions of LHC Run 2[66].

4.3.2. Muons

Muons behave differently than other particles as they go through the detector. They act as minimum-ionizing-particles (MIPs) throughout the calorimeter. The Muon Spectrometer (MS), Section 3.2.5, specializes in precision measurements of muons. The Inner Detector (ID) plays a pivotal role in the identification of muons as it offers an independent measure of the muon characteristics. Reconstructing muons use a specific set of variables as well[67]. These variables include q/p significance: the difference in the ratio of track charge and momentum measured with the ID and MS, ρ' : the difference between the transverse momenta measured with the ID and MS, and the χ^2 of the combined track fit using tracks from both the ID and MS.

Muons are separated out into four separate types depending on their interactions with the various subdetectors. The best muon candidates are combined muons which use hits in the MS to trace back to a track in the ID to reconstruct the entire muon track. Segment-tagged muons are muon candidates that leave a track in the ID but only a segment in the MS instead of a full track, this can occur because of the

muon having low p_T or crossing through a region of the MS with reduced acceptance. Extrapolated muons require only tracks in the MS and are used in regions of η, ϕ phase space that the ID does not cover. Calorimeter-tagged muons are muons identified by MIPs in the calorimeters and are used to find muons that cross the ID and MS in regions where cabling might prevent particle detection.

Muons also have their own set of isolation criteria which is track-based $p_T^{\text{varcone}0.3}$, with a cone of $\Delta R = \min(0.3, 10 \text{ GeV}/p_T)$. Similar to electrons various working points are available for at the analysis level for muons. These working points are named similarly: Loose, Medium, Tight, and High- p_T in order of background rejection.

High p_T jets that punch through the hadronic calorimeter can leave tracks in the MS which could be identified as muons. These would be identified as a bad or a fake muon because of the high hit multiplicities they leave in the MS as opposed to a single track left by a muon as it is a MIP. Another source of bad muons is a mis-measured ID track that gets incorrectly matched to segments in the MS. Fake muons are a source of fake missing transverse energy, \cancel{E}_T

4.3.3. Photons

Photons behave very similarly to electrons in the calorimeter in that they produce an electromagnetic shower in the calorimeter. However, they are neutrally charged particles meaning that they should not leave a track in the ID as they do not bend and produce bremsstrahlung photons travelling through the magnetic field. Prompt photons pair-produce electrons in the tracker but this process can be picked out as the associated cluster in the electromagnetic calorimeter is matched to two opposite charged tracks. This process is called a converted photon. Unconverted photons have no matching tracks associated to an electromagnetic cluster.

Category	Description	Name	<i>loose</i>	<i>tight</i>
Acceptance	$ \eta < 2.37$, with $1.37 \leq \eta < 1.52$ excluded	-	✓	✓
Hadronic Leakage	Ratio of E_T in the first sampling layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta $ or $ \eta > 1.52$)	R_{had_1}	✓	✓
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	R_{had}	✓	✓
EM Middle Layer	Ratio of the energy in $3 \times 7 \eta \times \phi$ cells over the energy in 7×7 cells centered around the photon cluster position	R_η	✓	✓
	Lateral shower width, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	ω_{η_2}	✓	✓
	Ratio of the energy in $3 \times 2 \eta \times \phi$ strips, over the energy of 3×6 cells centered around the photon cluster position	R_ϕ		✓
EM Strip Layer	Lateral shower width, $\sqrt{(\sum E_i(i - i_{\max})^2)/(\sum E_i)}$, where i runs over all strips in a window of $3 \times 2 \eta \times \phi$ strips, and i_{\max} is the index of the highest-energy strip calculated from three strips around the strip with maximum energy deposit	$\omega_s 3$		✓
	Total lateral shower width $\sqrt{(\sum E_i(i - i_{\max})^2)/(\sum E_i)}$, where i runs over all strips in a window of $20 \times 2 \eta \times \phi$ strips, and i_{\max} is the index of the highest-energy strip measured in the strip layer	$\omega_s \text{ tot}$		✓
	Energy outside the core of the three central strips but within seven strips divided by energy within the three central strips	f_{side}		✓
	Difference between the energy associated with the second maximum in the strip layer and the energy reconstructed in the strip with the minimum value found between the first and second maxima	ΔE_s		✓
	Ratio of the energy difference between the maximum energy deposit and the energy deposit in the secondary maximum in the cluster to the sum of these energies	E_{ratio}		✓
	Ratio of the energy in the first layer to the total energy of the EM cluster	f_1		✓

TABLE 4.1. Photon identification variables used for *loose* and *tight* photon identification, taken from [68]

Prompt photons produce narrower energy deposits in the electromagnetic calorimeter and have smaller leakage into the hadronic calorimeter compared to background photons. The energy contained within narrow structure in $\eta \times \phi$ strips compared to the energy contained in a larger section can help pickout prompt from non-prompt photons [68]. Cuts on this and the other variables listed in Table 4.1 are tuned to reduce dependency of identification efficiency on the pileup conditions of Run 2.

4.3.4. Jets

Contrasting with electromagnetic showers produced by electrons and photons, hadronic showers form through QCD processes. Quarks very quickly undergo showering by emitting gluons which further produce quark-antiquark pairs in analogy to the photons and pair produced electron-positron pairs of electromagnetic showers. When quarks have enough energy they hadronize by producing bound states of particles. These particles are typically pions or mesons that are measured by the ATLAS detector. The top quark is the only quark that decays before hadronization because it decays so fast (5×10^{-25} s). The spray of hadrons coming from a quark from the initial interaction is called a jet and is a collection of detector objects that are traced back and assigned to the quark(s) in the final state of the interaction. The algorithms that do this are called jet-finding algorithms and pictoral representations of the same event reconstructed with four various algorithms is shown in Figure 4.10.

The jets used in this analysis use the anti- k_T algorithm [69] with a radius parameter $R = 0.4$. Jets are not physical objects but collections of them so how they are defined can change the physics objects that are eventually analyzed. The

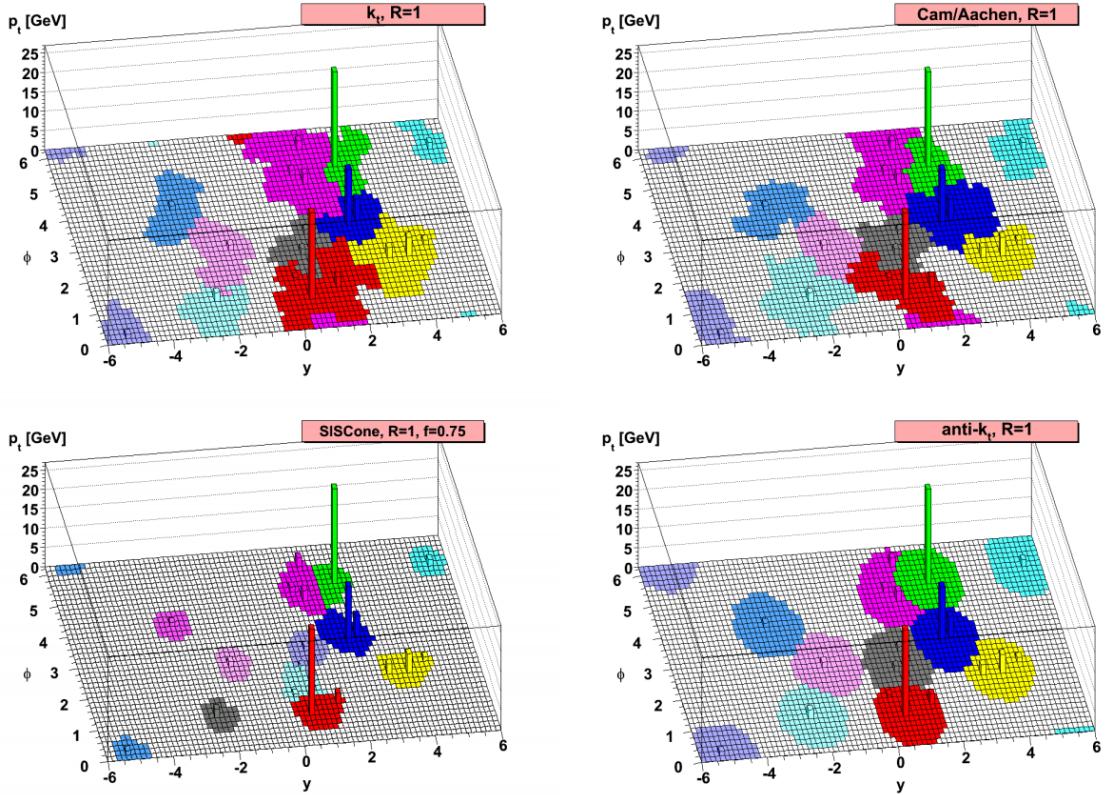


FIGURE 4.10. A sample parton-level event with many random soft jet objects, clustered with four different jets algorithms, illustrating the areas of the resulting hard jets. For k_T and Cambridge/Aachen the detailed shapes are in part determined by the specific set of ghosts used, and change when the ghosts are modified [69]

$\text{anti-}k_T$ algorithm is preferred because it is infrared and collinear safe. Infrared safe jet algorithms do not merge two jets with a soft emission between them. Adding or removing a soft term between two jets should not change what objects are called jets. Collinear safe jet algorithms do not change the jet collection if you split or merge the high transverse momentum particles. Another added benefit of the $\text{anti-}k_T$ jet finding algorithm is that it gives roughly circular jet objects which simplifies calculating the energy density making calibrating the physics object simple.

The anti- k_T algorithm calculates the distance between an object i and all possible jet objects j (d_{ij}) and the beam (d_{iB})

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R}, \quad d_{iB} = k_{ti}^{2p}$$

where k_{ti} is the transverse momentum, Δ is the distance between the objects, and $p = -1$. This is a general form for the type of algorithm, the inclusive k_T algorithm has a p value of 1 and the inclusive Cambridge/Aachen algorithm has a p value of 0 [70]. The algorithm then follows that if d_{ij} is smaller than d_{iB} then objects i and j are merged, otherwise i is labeled as a jet and removed from the list of entries of possible jet objects. This is repeated for all entries in the list of possible jet objects.

Jet cleaning is also applied to remove events with jets built from known noisy parts of the calorimeter due to particular calorimeter cells or non-collision background in those areas [71]. To reduce selecting jets that originate from pileup interactions another requirement on the jet object is made on the jet vertex tagger [72, 73] as follows:

1. For jets with $20\text{GeV} < p_T < 60\text{GeV}$ and $|\eta| < 2.4$: if any jet is bad AND that jet is not marked as pileup by JVT, then reject the event
2. For jets with $20\text{GeV} < p_T < 60\text{GeV}$ and $|\eta| \geq 2.4$: if any jet is bad, then reject the event
3. For jets with $p_T \geq 60\text{GeV}$: if any jet is bad, then reject the event

4.3.4.1. B-Jets

While jets originate from any quark jets coming from b quarks can be identified due to their decay products. B quarks hadronize into b-hadrons which have a

relatively long lifetime compared to many other hadrons produced from light quarks. The longer lifetime and the relativistic speeds the hadrons travel at mean the particle travels a measureable distance before it decays ($400 - 500\mu m$)[74]. This means that the vertex reconstructed from the energy coming from a b hadron decay can be traced back to a point that does not correspond to the primary vertex of the event. A pictoral representation of a b quark decay can be seen inf Figure 4.11 and the b jet vertex is called the secondary vertex.

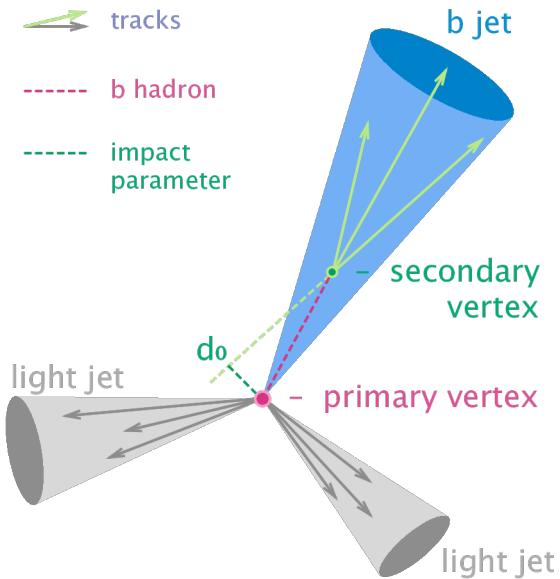


FIGURE 4.11. Pictoral representation of an event with a b jet showing the secondary vertex and impact parameter [75]

In addition to the secondary vertex other variables are helpful at identifying jets coming from b quarks. Back tracing the tracks within the displaced vertex the minimum distance between the track and the interaction point can be measured, the impact parameter. Reconstructing the decay chain of the jet is also used in determining the providence of the jet. This information is used in a multivariate analysis (MVA) to identify jets coming from b-quarks and reject jets coming from light quarks.

The MVA used in this analysis is the MV2c10 is the discriminant used for bjet identification [76]. The output distributions for various flavors of jets as well as background rejection and signal efficiency plots are shown in Figure 4.12. The c10 in the algorithm name refers to the background training sample of the MVA consisting of a 10% fraction of c-jets. The 77% efficiency fixed-cut working point for b-jet identification was chosen for this analysis, discussed in Section 5.6. Differences in efficiency of b-tagging between data and simulation is taken into account with working point specific scale factors provided by the ATLAS Flavour Tagging Combined Preformance group.

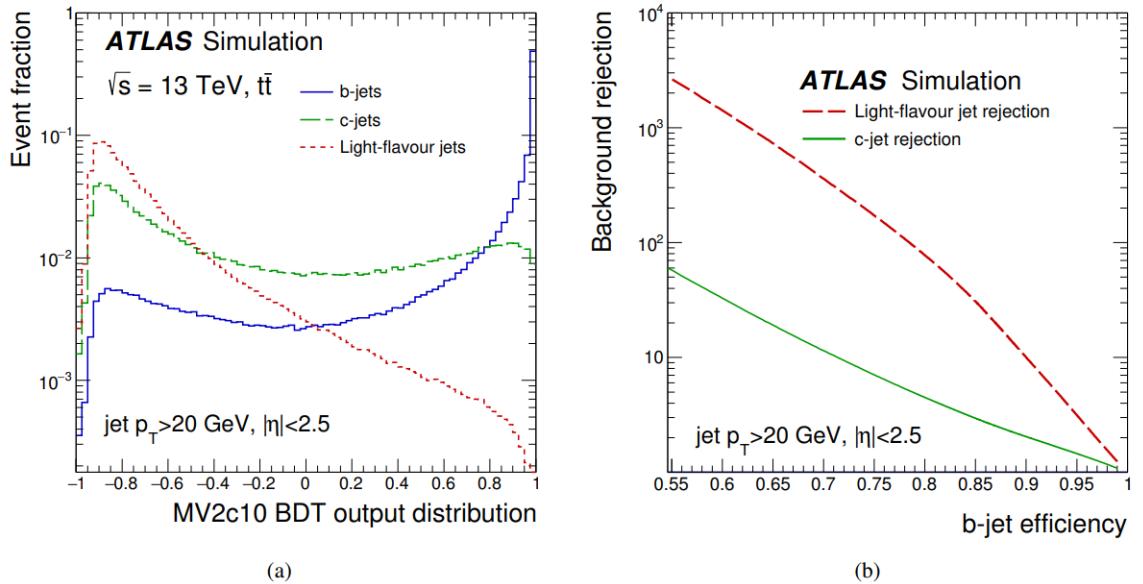


FIGURE 4.12. The MV2c10 output for b,c, and light flavored jets in simulated $t\bar{t}$ and the background rejection as a function of the b-jet efficiency [77]

4.3.5. Missing Transverse Energy

The remaining signal object that has yet to be discussed it the neutrino coming from the W boson decay. Neutrinos do not interact with the detectors as they pass through the ATLAS detector. The only way to measure any properties of the neutrino

in ATLAS events is to use conservation of momentum. As previously mentioned the collision energy is unknown as partons do not carry a consistent fraction of the beam proton energy. However, in the transverse plane to the beamline the total momentum is known to be very small. Before the collision there is on the order of 1 GeV of momentum in the transverse plane. Knowing the state before the collision we know that the total transverse momentum of the collision products should be approximately zero.

Any imbalance in the momentum is referred to as Missing Transverse Momentum (\cancel{E}_T). The negative vector sum of all reconstructed objects plus an additional soft term are used to calculate the missing energy in the x-plane and the y-plane[78]. A magnitude and azimuthal angle are calculated to give the \cancel{E}_T vector in the transverse plane but this does not directly correspond to a neutrino which also has a momentum in the z direction.

4.3.5.1. Neutrino Reconstruction

In this analysis the signal region contains only one source of missing energy so all of the missing energy can be used to reconstruct a neutrino object. There is an ambiguity in the choice of the neutrino z-momentum. To find the z-momentum a χ^2 minimization is done:

$$\begin{aligned}\chi^2 &= \chi_{\text{SMTop}}^2 + \chi_W^2 \\ \chi^2 &= \frac{(m_{\text{bjet},l,\nu} - m_t)^2}{\sigma_{\text{SMTop}}^2} + \frac{(m_{l,\nu} - m_W)^2}{\sigma_W^2}\end{aligned}$$

The widths σ_{SMTop} and σ_W^2 are determined from signal Monte Carlo. The event objects are combined to calculate the invariant mass of the top quark (the combination of the b-jet, lepton and neutrino) and the W boson (combination of the lepton and

neutrino). This is done while varying the z momentum of the neutrino. The neutrino momentum that corresponds to the smallest χ^2 value is given assigned to the neutrino object for further use in the analysis. The χ^2 values were also used as a discriminating variable and fed into a neural network (Section 5.6) with χ_W^2 having the stronger separation between signal and background.

CHAPTER V

SEARCH STRATEGY

5.1. Major Backgrounds

5.2. Event Reconstruction

5.3. Data and Simulation Event PreSelection

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CHAPTER VII

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