SEARCH FOR Z' PRODUCTION IN 4 B-TAGGED JET FINAL STATES IN PROTON-PROTON COLLISIONS

A Dissertation

by

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Chair of Committee,	Chair Name
Committee Members,	Committee Member 1
	Committee Member 2
	Committee Member 3
Head of Department,	Head of Department

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ABSTRACT

This is the first numbered page, lower case Roman numberal (ii). Page numbers are outside the prescribed margins, at the bottom of the page and centered; everything else is inside the margins.No bold on this page (Exception: heading ABSTRACT is bold if major headings are bold. *This LaTeX template applies to this exception*).

Text begins two double spaces below the major heading. Recommended length of text is no more than 350 words. Vertical spacing is double spaced or space-and-a-half. (*This LaTeX template applies double space for this ABSTRACT.*) The same margin settings and text alignment are followed else where in this thesis. There should be no numbered references or formal citations in ABSTRACT.

The content of this ABSTRACT provides a complete, succinct snapshot of the research, addressing the purpose, methods, results, and conclusions of the research. As a result, it should stand alone without any formal citations or references to chapters/sections of the work. To accomodate with a variety of online database, images or complex equations should also be avoided.

The next pages are Dedication, Acknowledgments, Contributors and Funding Sources, and Nomenclature. Of these, Contributors and Funding Sources is required. The rest are optional.

DEDICATION

To my mother, my father, my grandfather, and my grandmother. To see what happens with multiple lines, I extend this next part into a second line.

ACKNOWLEDGMENTS

This section is also optional, limited to four pages. It must follow the Dedication Page (or Abstract, if no Dedication). If listing preliminary pages in Table of Contents, include Acknowledgments. Heading (ACKNOWLEDGMENTS) is bold if major headings are bold. It should be in same type size and style as text. So does vertical spacing, paragraph style, and margins. Also, ensure that the spelling of "acknowledgments" matches throughout the text and the table of contents.

I would like to thank the Texas A&M University Office of Graduate and Professional Studies to allow me to construct this LaTeX thesis template. Special thanks to JaeCee Crawford, Amy Motquin, Ashley Schmitt, Rachel Krolczyk, and Roberta Caton for carefully reviewing this material.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis (or) dissertation committee consisting of Professor XXXX [advisor – also note if co-advisor] and XXX of the Department of [Home Department] and Professor(s) XXXX of the Department of [Outside Department].

The data analyzed for Chapter X was provided by Professor XXXX. The analyses depicted in Chapter X were conducted in part by Rebecca Jones of the Department of Biostatistics and were published in (year) in an article listed in the Biographical Sketch.

All other work conducted for the thesis (or) dissertation was completed by the student independently.

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NOMENCLATURE

OGAPS	Office of Graduate and Professional Studies at Texas A&M University
B/CS	Bryan and College Station
TAMU	Texas A&M University
SDCC	San Diego Comic-Con
EVIL	Every Villain is Lemons
EPCC	Educator Preparation and Certification Center at Texas A&M University - San Antonio
FFT	Fast Fourier Transform
ARIMA	Autoregressive Integrated Moving Average
SSD	Solid State Drive
HDD	Hard Disk Drive
O&M	Eller Oceanography and Meteorology Building
DOS	Disk Operating System
HDMI	High Definition Multimedia Interface
L^1	Space of absolutely Lebesgue integrable functions; i.e., $\int \lvert f\rvert < \infty$
L^2	Space of square-Lebesgue-integrable functions, i.e., $\int \lvert f\rvert^2 < \infty$
$PC(S)$	Space of piecewise-continuous functions on S
GNU	GNU is Not Unix
GUI	Graphical User Interface
PID	Principal Integral Domain
MIP	Mixed Integer Program

LP	Linear Program

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1. INTRODUCTION AND LITERATURE REVIEW

1.1 Author's Message to the Student Using This Template For Their Thesis or Dissertation

Howdy! This is the template for theses and dissertations written using LaTeXfor submission at Texas A&M University. The Office of Graduate and Professional Studies (OGAPS) is here to guide you in submitting your thesis or dissertation. This template shows the many features of LaTeX, with many more available to the user.

There are numerous guides, references, and tutorials available on the Internet to help you. If you are stuck, don't be afraid to conduct a Google search for your issue, or you can contact me at szroberson@exchange.tamu.edu or ogaps-latex@tamu.edu.

1.1.1 Brief Usage of the Template

This template is intended for use by STEM[1] students. If you are not a STEM student, this template is likely not for you.

The advantage of using this template over the Microsoft Word templates are numerous. First, there is a lot of control granted to the user in how the document looks. Of course, you are expected to still follow the guidelines set forth in the TAMU Thesis Manual. This template takes care of the margins, heading requirements, and front matter ordering for you.

Software to Install

MikTeX or **ProTeXt** is the free software recommended for Windows PC users to compile your LaTeX document. To compile for this document, XeLaTeX compiling engine is used. There is currently an issue in which the package xetex-def does not install; see the file README.txt for a solution. Another software called **JabRef** is also recommended for bibliography/reference management; its usage is similar with EndNote.

[1]Science, Technology, Engineering, and Mathematics. This is an example of a footnote. You can see that it is numbered and appended at the end of the page. Also, you can see the effect of having a multiline footnote.

Procedure to Compile LaTeX Document

This template (and consequently, your document) will be compiled using XeLaTeX. To compile your document, do the following[2]:

- In TeXstudio, go to the Tools menu, then select Commands, and click XeLaTeX.
- In Texmaker, go to the Tools menu and select XeLaTeX.
- For other editors, consult the help files included with the editor.

To view the output after the program is done compiling, press F7 in TeXstudio and TeXmaker or the appropriate hotkey for other editors. Be sure that the document is not open in another PDF reader, for your editor will not display it.

1.1.2 How to Fill This Document

The document structure is organized in the main .tex file, TAMUTemplate.tex, which has the same name as the output PDF file. Content in each section is in the data folder. You can open the .tex files under the data folder to modify. Four sections are added initially. To add in more sections into the LaTeXdocument, open the TAMUTemplate.tex file and go to **line 130** you can just delete the content in the data folder and fill your documents and then compile under TAMUTemplate.tex.)

1.1.3 Reference Usage and Example

This subsection tests the usage of references. The book[**?**] is referred in this way. Actually, the option is available for you to change the default way how reference appears. The default and most commonly used option [**?**] is displayed here [**?**].

Unrelated citations are referred here for the test of reference section only[**?**]. If you find that the reference [**?**] has more items than you need [**?**], question marks will show up in place of a reference handle, like these [**?**].

[2]Notice here that I also show off the itemize environment for unordered lists. Ordered lists use the enumerate environment.

1.1.4 Equations, Formulas, and Other Really Cool Math Things That LaTeX Can Do

Equations can be written in LaTeX in one of two ways. First, you can have material displayed inline by enclosing the desired statement in dollar signs. For example, $e^{i\pi} + 1 = 0$ is an inline math expression. Some longer expressions, especially those including sums, integrals, or large operators and objects can be displayed centered on their own line. In this **math mode**, you enclose the desired material in square brackets. For example,

$$\sum_{j=1}^{n} \int f_j \, dx = \int \sum_{j=1}^{n} f_j \, dx$$

is a math mode expression. We can also have a series of expressions aligned at a symbol. This is particularly useful when you are showing details in solving an equation or evaluating an integral. The next block shows off the *align** environment. We use it here to show a distributive property of set intersections over unions. Observe how each line is aligned to the biconditional symbol. This makes reading steps easier, since a reader can go line by line and determine why each step is justified.

$$\begin{aligned} x \in A \cap \bigcup_j B_j &\iff x \in A \ \wedge \ x \in \bigcup_j B_j \\ &\iff x \in A \ \wedge \ x \in B_k \text{ for some k} \\ &\iff x \in \bigcup_j A \cap B_j \end{aligned}$$

There are many more commands and features available, but this document is too small to contain them.[3] Many guides are available on the Internet for your use.

1.1.5 A Test Section

This is just a test. Below is a figure displaying some Haskell code in a compiler.

[3] Yes, I pulled a Fermat. But really, a Google search will likely help you find what you need to do.

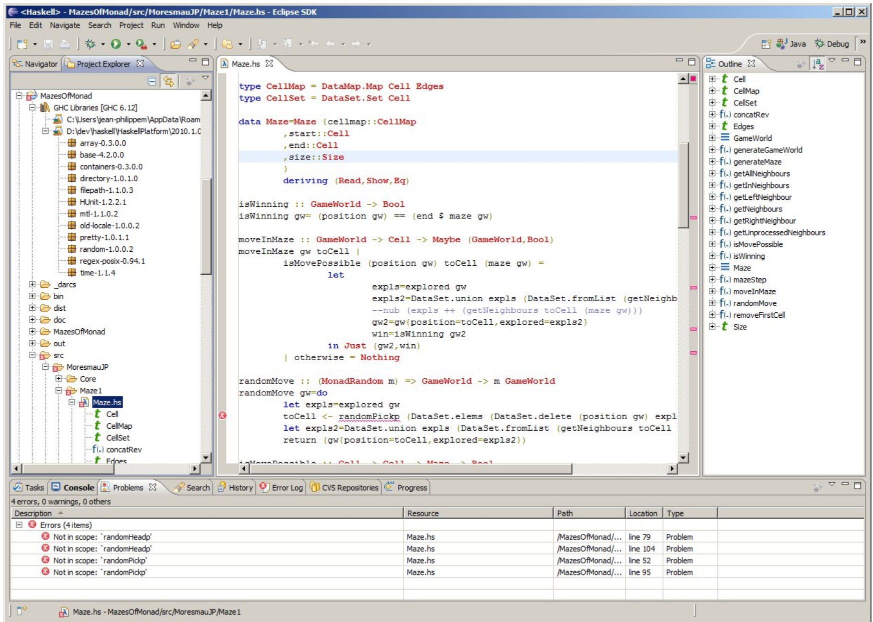


Figure 1.1: Some Haskell code in a compiler.

This template has been designed for use in modern systems, but can perhaps be adapted to work on older systems, such as Windows 95. Below is a screenshot of a DOSBox console, an MS-DOS emulator designed to work on several platforms. Windows 95 can be installed into DOSBox, but it is not suggested.

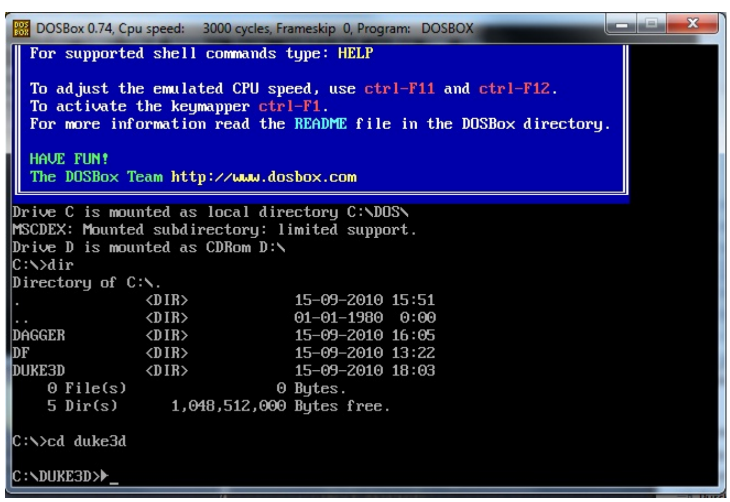


Figure 1.2: The DOSBox console running in Windows 7. The contents of the mounted directory C: are displayed, with the active subdirectory DUKE3D.

1.2 Specifications in This TAMU LaTeX Template

All requirements for theses can be found in the most recent version of the Thesis Manual, available at the OGAPS website. The Thesis Office will be happy to assist you if you have questions about formatting. Questions specific to LaTeX should be directed to `ogaps-latex@tamu.edu`.

A common question students ask is the placement of a copyright statement at the beginning of a section with reprinted material from a previously printed source. The screenshot below describes how to achieve this. Check the instruction files for more details.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                            SECTION II
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

\renewcommand*{\thefootnote}{\fnsymbol{footnote}}

\chapter[PAGES WITH A FIGURE, A TABLE AND AN EQUATION]{PAGES WITH A FIGURE, A TABLE AND AN EQUATION
\footnote{I am allowed to do this}}

\renewcommand*{\thefootnote}{\arabic{footnote}}
```

Figure 1.3: The inclusion of a copyright statement as a footnote. The lines in yellow help to change to footnote marking scheme.

1.2.1 Another Test Section

There should be things here.

1.2.1.1 Test

Hello, is it me you're looking for?

1.2.1.2 Test 2

There are more things to do.

1.2.2 Yet Another One

She called me late last night to say she loved me so. We insert a slew of figures in the remainder of the document to test the look of the List of Figures.

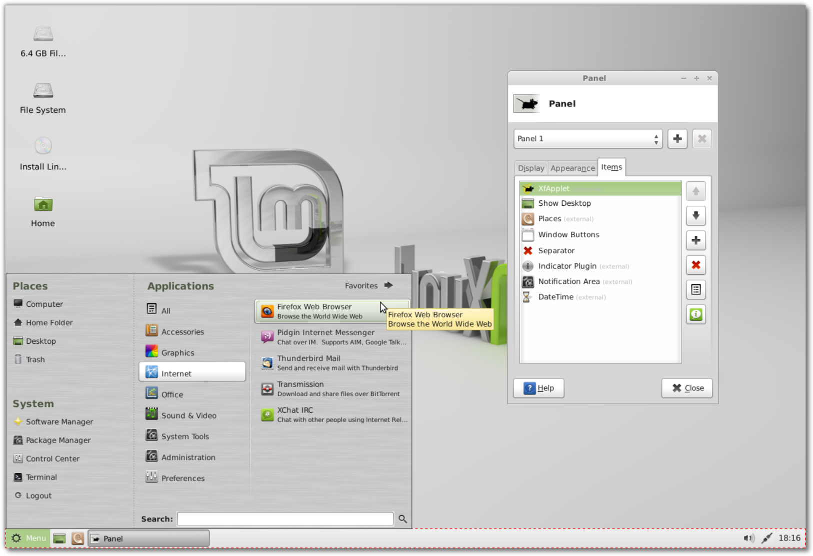


Figure 1.4: Linux Mint 13 with the XFCE desktop environment.

Another figure follows below.

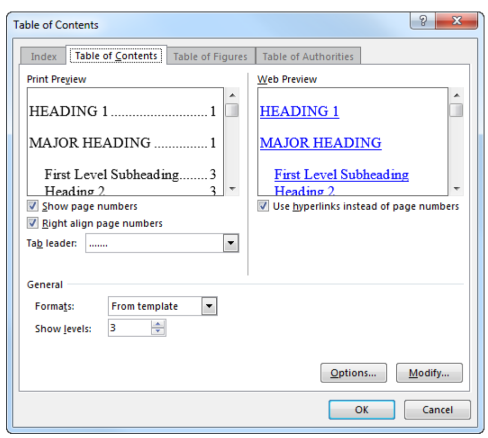
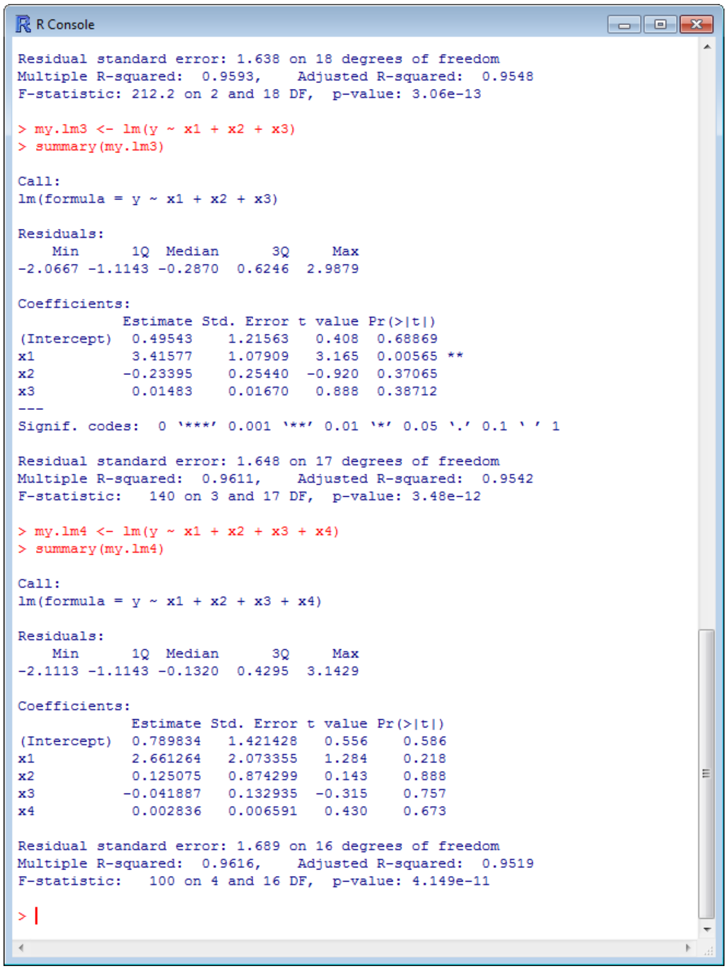


Figure 1.5: The “Table of Contents" dialog box in Microsoft Word. This must be accessed to properly generate the Table of Contents when using the Recommended Template.

Yet another figure follows - the last for this section.



```
Residual standard error: 1.638 on 18 degrees of freedom
Multiple R-squared:  0.9593,    Adjusted R-squared:  0.9548
F-statistic: 212.2 on 2 and 18 DF,  p-value: 3.06e-13

> my.lm3 <- lm(y ~ x1 + x2 + x3)
> summary(my.lm3)

Call:
lm(formula = y ~ x1 + x2 + x3)

Residuals:
    Min      1Q  Median      3Q     Max
-2.0667 -1.1143 -0.2870  0.6246  2.9879

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.49543    1.21563   0.408  0.68869
x1           3.41577    1.07909   3.165  0.00565 **
x2          -0.23395    0.25440  -0.920  0.37065
x3           0.01483    0.01670   0.888  0.38712
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.648 on 17 degrees of freedom
Multiple R-squared:  0.9611,    Adjusted R-squared:  0.9542
F-statistic:   140 on 3 and 17 DF,  p-value: 3.48e-12

> my.lm4 <- lm(y ~ x1 + x2 + x3 + x4)
> summary(my.lm4)

Call:
lm(formula = y ~ x1 + x2 + x3 + x4)

Residuals:
    Min      1Q  Median      3Q     Max
-2.1113 -1.1143 -0.1320  0.4295  3.1429

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.789834   1.421428   0.556    0.586
x1           2.661264   2.073355   1.284    0.218
x2           0.125075   0.874299   0.143    0.888
x3          -0.041887   0.132935  -0.315    0.757
x4           0.002836   0.006591   0.430    0.673

Residual standard error: 1.689 on 16 degrees of freedom
Multiple R-squared:  0.9616,    Adjusted R-squared:  0.9519
F-statistic:   100 on 4 and 16 DF,  p-value: 4.149e-11

>
```

Figure 1.6: Linear regression on three (top) and four (bottom) independent variables in base R.

1.2.3 No Surprises Here

Insert another song lyric here.

2. THEORETICAL FRAMEWORK

2.1 The Standard Model

Particle physics is the study of the fundamental constituents of matter and the forces between them. For more than 40 years these have been described by the so-called standard model of particle physics (SM), which provides, at least in principle, a basis for understanding most particle interactions, with the only exception of gravity.

The SM can be understood as a gauge theory combining the theory of electroweak interactions(EW) and quantum chromodynamics(QCD), or $SU(3) \times SU(2) \times U(1)$. Several experiments have validated this theory to a great accuracy. However, we know the SM to be incomplete as it does not provide answers to questions like the origin of neutrino masses, the existence of dark matter, or that of dark energy.

2.2 Structure and Particle Content

In this section, the particle content of the SM will be intriduced, along with the various force carriers. In the following section, the specifics of particle-particle interactions will be explained in detail.

Elementary particles have an associated quantum number call spin, which allows for particle classification in terms of this quantity as fermions and bosons.

2.2.1 Fermions

Fermions are elementary particles with half-integer spin. They constitute the matter content of the SM, which accounts for 12 named fermions, which interact via the weak and electromagnetic force (with the exception of neutrinos). Also, they obey Fermi-Dirac statistics and the Pauli exclusion principle, meaning that no two fermions may be described by the same quantum numbers. Each fermion has its own anti-particle with the same mass but opposite quantum numbers.

The particle content of the SM can be divided into two additional categories of six fermions each, i.e. quarks and gluons. the quarks, which must bind together due to their strong force interaction and the leptons, which can exist independently. Quarks are known to bind into triplets and doublets, called baryons and mesons, respectively. Leptons come into three flavors, each one corresponding to a doublet where the electron, muon and tau are paired with a neutrino.

Moreover, fermions are grouped into 3 families or generations of 4 particles (2 quarks and 2 leptons), according to their masses. Each subsequent generation being a heavier version of the previous generation, with the same quantum numbers (neutrinos may have a different mass order). Therefore, the particle formed from Generation I particles are usually more stable and long-lived than those made from Generation III particles. Protons and neutrins themselves are made up of up and down quarks.

2.2.2 Bosons

The SM bosons are the mediators of the interaction between the matter content of the SM, but also within themselves. They have integral spin quantum number and follow Bose-Einstein statistics. There are 5 named bosons, the gluons, photons, and W and Z with spin 1 since they go with vector fields, and the Higgs boson which corresponds to a scalar field and therefore has spin 0.

2.3 Particle Interactions

The interactions of the particles described in the previous section can be described in the mathematical framework of the gauge field theory. Three of the four fundamental forces of nature are described in the SM (electromagnetism, the strong and the weak force). Each force has its own corresponding charge, (i.e. electric charge, color or flavor) and has an associated boson as mediator.

Modern theories describe these forces in terms of Quantum fields, namely QED, QCD and the unified electroweak quantum field theory. One feature all these theories have in commmon is that they are all gauge invariant. Gauge theories are of particular interest to particle physicists because their invariance under gauge transformations result in conservation laws and outline the rules of particle interactions, as we will see in the remainder of the section.

2.3.1 Quantum Electrodynamics

Quantum Electrodynamics (QED) describes the dynamics of the electromagnetic interaction. In this theory, spin 1/2 particles or fermions are represented by fields. It was the first discovered example of gauge symmetry, and it was developed from classical field theory, thus, the dynamics of a given system is completely specified by its Lagrangian.

If we start with the Lagrangian density for a free electron of mass m:

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi \tag{2.1}$$

where γ^{μ} are the gamma matrices, ϕ is a 4-component column vector representing the elctron wave function and $\bar{\psi} = \psi^{\dagger}\gamma^{0}$. We will see that the Lagrangian is invariant under a global U(1) transformation when:

$$\psi \rightarrow \psi' = e^{-i\alpha}\psi \tag{2.2}$$

while the parameter α is kept a constant. If instead, α is allowed to vary as a function of spacetime, the Lagrangian is not invariant under the local transformation anymore.

In order to restore local gauge invariance, a gauge field A_{μ} representing the photon and the covariant derivative $D_{\mu} = \partial_{\mu} + iqA_{\mu}$ are introduced. The latter has the same transformation properties as the electron field and is chosen to replace ∂_{μ}.

After introducing these modifications, the Lagrangian takes the form:

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{2.3}$$

where $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$ is the electromagnetic field strenght tensor. As a result of local gauge invariance, the Lagrangian now includes the electron-photon interaction $e^{+}e^{-}\gamma$ and a term representing the photon kinetic energy.

Finally, the Lagrangian can be generalized to include the muon and tau leptons:

$$\mathcal{L} = \sum_i \bar{\psi}_i(i\gamma^\mu D_\mu - m_i)\psi_i - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{2.4}$$

where $i = e, \mu, \tau, u, d, c, s, t, b$.

2.3.2 Electroweak Interaction

The electroweak interaction is based on a local $SU(2) \times U(1)$ gauge symmetry where L and Y are the generators of the symmetry. As a result, electromagnetic and weak interactions are unified into a single interaction. Also, just like in Section, the requirement of local gauge invariance leads to the introduction of gauge fields and determined the interactions mediated by those fields.

The left-handed components of the elctron neutrino and electron are grouped into an SU(2) doublet. Since the right-handed component of the electron is invariant under SU(2), it is placed in a singlet, i.e.:

$$L_e = (\nu_e e_L), e_R \tag{2.5}$$

And so on for the heavier generations of leptons. So far, there is no evidence of right-handed neutrinos in the SM.

The dynamic portion of the electroweak Lagrangian for first generation leptons can be represented by:

$$\mathcal{L}^e_{dyn} = L^\dagger_e \sigma^\mu i\partial_\mu L_e + e^\dagger_R \sigma^\mu i\partial_\mu e_R \tag{2.6}$$

where $\sigma = (\sigma^0, \sigma^1, \sigma^2, \sigma^3)$, $\sigma = (\sigma^0, -\sigma^1, -\sigma^2, -\sigma^3)$, σ^0 is the identity matrix, and the σ^i are the Pauli matrices. This Lagrangian is invariant under the global transformation:

$$L \rightarrow L' = e^{i\theta} UL \tag{2.7}$$

$$e_R \rightarrow e'_R = e^{2i\theta} e_R \tag{2.8}$$

where

$$U = e^{-ia^k\sigma^k} \tag{2.9}$$

and θ and a^k are real numbers parameterizing the transformation. However, the Lagrangian is not invariant under a transformation where these parameters are allowed to vary as a function of space-time, i.e. a local transformation.

Following the same reasoning as in the previous section, we can introduce gauge fields and replace the space-time derivatives with an appropiately chosen covariant derivative. This time, we introduce a U(1) gauge field $B_\mu(x)$ and three SU(2) gauge fields $W_\mu(x) = W_\mu^k(x)\sigma_k$. Such fields must transform as

$$B_\mu(x) \to B'_\mu(x) = B_\mu(x) + \frac{2}{g_1}\partial_\mu\theta(x) \tag{2.10}$$

$$W_\mu(x) \to W'_\mu(x) = U(x)W_\mu(x)U^\dagger(x) + \frac{2i}{g_2}(\partial_\mu U(x))U^\dagger(x) \tag{2.11}$$

where g_1 and g_2 are dimensionless parameters of the theory, the coupling strengths of the interactions. The necessary covariant derivatives are given by

$$D_\mu L_e = (\partial_\mu + i\frac{g_1}{2}YB_\mu + i\frac{g_2}{2}W_\mu)L_e \tag{2.12}$$

$$D_\mu e_R = (\partial_\mu + i\frac{g_1}{2}YB_\mu)e_R \tag{2.13}$$

where Y is the hypercharge operator, whose values are listed in Table

These covariant derivatives transform according to the same rule as the fields themselves. The Lagrangian Eq becomes

$$\mathcal{L}^e_{dyn} = L_e^\dagger\tilde{\sigma}^\mu iD_\mu L_e + e_R^\dagger\sigma^\mu iD_\mu e_R - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \sum_{i=1}^{3}\frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} \tag{2.14}$$

where $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ and $W_{\mu\nu} = [\partial_\mu + (\frac{ig_2}{2})W_\mu]W_\nu - [\partial_\nu + (\frac{ig_2}{2})W_\nu]W_\mu$ are the field strength tensors, allowing for the Lagrangian to be locally gauge invariant.

The mediators of the electroweak force are the physical bosons $W^\pm$, the Z and the photon. All these are combinations of the gauge fields in the following way.

The $W^\pm$ are linear combinations of the W_1 and W_2, which are electrically chargede and given by

$$W^\pm_\mu = \frac{W^1_\mu \mp iW^2_\mu}{\sqrt{2}} \tag{2.15}$$

The W_3 and B gauge fields are electrically neutral. The physical Z and photon are linear combinations of these fields, given by

$$Z_\mu = W^3_\mu cos\theta_W - B_\mu sin\theta_W \tag{2.16}$$

$$A_\mu = W^3_\mu sin\theta_W - B_\mu cos\theta_W \tag{2.17}$$

where the Weinberg angle θ_W is defined by $sin\theta_W = g_1/\sqrt{g_1^2 + g_2^2}$.

Now, the interactions contained in the Lagrangian only couple the $W^\pm$ to the left-handed lepton components, but couple the Z and photon to both the left- and right-handed components.

We can also see from here that the interaction strength is equal to the electromagnetic charge unit e, i.e. $g_2 sin\theta_W = g_1 cos\theta_W = e$.

Finally, in order to include second and third generation leptons, the Lagrangian generalizes to

$$\mathcal{L}^l_{dyn} = \sum_{leptons} (L^\dagger_e \tilde{\sigma}^\mu iD_\mu L_e + e^\dagger_R \sigma^\mu iD_\mu e_R) - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \sigma^3_{i=1} \frac{1}{4} W^i_{\mu\nu} W^{i\mu\nu} \tag{2.18}$$

Quarks are included in the electroweak sector in a similar manner. The left-handed components of the u and d quark are place in SU(2) doublets, and the right-handed components in singlets.

$$Q_u = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \tag{2.19}$$

Two additional doublets and four singlets exist for the second and third generation quarks. The covariant derivatives acting on the quark fields are the same as those which act on the lepton fields, but the quarks have different weak hypercharge assignments from the leptons. Therefore, the dynamic portion of the u and d quark Lagrangian is given by:

$$\mathcal{L}^q_{dyn} = \sum_{quarks} Q_u^\dagger \tilde{\sigma}^\mu i D_\mu Q_\mu + u_R^\dagger \sigma^\mu i D_\mu u_R + d_R^\dagger \sigma^\mu i D_\mu d_R \tag{2.20}$$

Again, the W bosons couple only to the left-handed quark kcomponents, while the Z and photon couple to the right-handed components as well.

The dynamic portion of the electroweak Lagrangian is a result of the addition of the lepton and quark components

$$\mathcal{L}^{EW}_{dyn} = \mathcal{L}^l_{dyn} + \mathcal{L}^q_{dyn} \tag{2.21}$$

Here, we should notice that a couple of symmetries arise from the form of the Lagrandian in Eq. If a U(1) transformation of the form $L_{e,\mu,\tau} \rightarrow e^{i\alpha} L_{e,\mu,\tau}$, $e, \mu, \tau_R \rightarrow e, \mu, \tau^{i\alpha} e, \mu, \tau_R$ leaves the Lagrangian invariant, which leads to conservation of lepton number. Additionally, a U(1) transformation multiplying all negatively (positively) charged fields by $e^{i\alpha}(e^{-i\alpha})$ leaves the Lagrangian invariant, and implies conservation of electric charge.

On the other hand, the EW Lagrangian is not invariant under charge conjugation C of a parity conservation P. Charge conjugation is the operation of changing the sign of all discrete quantum numbers, or equivalently exchanging all particles with antiparticles and vice-versa. A parity transformation is the inversion of spatial coordinates, $r \rightarrow -r$. The neutral current interactions, mediated by the Z and photon, preserve combined CP invariance. However, even combined CP symmetry is violated by weak current interactions, mediated by the $W^{\pm}$, in the quark sector. A third important potential symmetry is time reversal T, where $t \rightarrow -t$. Combined CPT invariance is required to mantain Lorentz invariance. Therefore, the breaking of CP also implied the breaking of T symmetry.

The SM can be understood in terms of its particle content, the so-called fermions and the mediators of the interactions

The matter content of the SM can be classified into two categories, according to the particle's spin. Particles with half-integer spin are referred to fermions, while those having integer spin are usually referred to as bosons.

Fermions follow Dirac-Fermi statistics interact electromagnetically, except for the neutrinos and can be further classified into leptons and quarks, which interact via the strong force.

Bosons follow Bose-Einstein statistics and provide the mechanism by which the matter particles, i.e. the fermions interact with each other. The gluon, photon, W, and Z bosons all have spin-1 and are responsible for the strong, electromagnetic, and weak interaction, respectively.

The final piece of the SM if the Higgs boson, which is the only spin-0 boson and is responsible for the masses of the other particles in the SM.

But how do these particles arise?

2.4 Lepton universality

One of the current assumptions of the SM is that electron, muon, and tau couplings are the same when interacting weakly. This is often referred to as lepton universality.

2.5 B-hadron anomalies

So far, no definite violation of this rule has been observed, but recent studies involving the decay rates of B mesons seem to challenge it. BaBar, LHCb and Belle experiments have reported anomalous deviations from SM in measurements of:

1. The angular distributions of the decay rate of $B \rightarrow K^{*}\mu^{+}\mu^{-}$.

2. The branching ratios $R_K = \frac{BR(B^{+} \rightarrow K^{+}\mu^{+}\mu^{-})}{BR(B^{+} \rightarrow K^{+}e^{+}e^{-})}$ and $R_{K^*} = \frac{BR(B^{+} \rightarrow K^{*}\mu^{+}\mu^{-})}{BR(B^{+} \rightarrow K^{*}e^{+}e^{-})}$.

Each of these results show a deviation from the expected SM value of 1 in the 2.4-2.6 σ range. These decay processes are very rare in the SM, making it hard to obtain a precise measurement. Also, a better understanding of the SM physics behind them (in terms of hadronic uncertainties) could also provide reconciliation with SM predictions. A more recent study combined the results for R_K and R_{K^*}, resulting in a 4σ deviation from the SM.

2.5.1 $b \to s$ quark transitions

This anomaly hints at the posibility that $b \to s$ quark transitions cannot be understood entirely within the SM framework.

Within the SM, the lowest order processes that could mediate the $b \to s$ quark transitions are at least of third order. Therefore, these processes are rarely observed.

2.6 The Z'

As an alternative, a possible explanation to the B-decay anomalies could postulate the existence of a new heavy neutral gauge boson, the Z'. Such a particle would couple to $b - s$ quarks and non-universally to leptons. In addition, it would be assumed to couple mostly to third generation quarks to explain why it has not been seen yet by any experiment.

2.6.1 Flavour-violating coupling δ_{bs}

In order to provide an explanation for B-decay anomalies, we need to consider the flavour-violating coupling δ_{bs}. Allowing the Z' boson to couple to s quarks in addition to b quarks results in two times more ways to produce the Z' and two times more ways for it to decay. A non-zero δ_{bs} will allow the Z's to be produced by b and $\bar{s}$ quarks (in addition to $b\bar{b}$ ones) and this significantly enhances the production cross section.

2.6.2 Lifetime calculation

2.6.3 4b Bottom Fermion Fusion

If we make the assumption that the Z' couples mostly to b quarks, the particle could have diagrams like the on on Figure, which we will refer to as Bottom Fermion fusion diagram (BFF) due to its similarity with Vector Boson Fusion (VBF) diagrams.

3. VERY, VERY, VERY LONG TITLE THAT FLOWS INTO A SECOND LINE FOR THE SAKE OF EXAMPLE

Notice that the title of this section is long - much longer than the others. When you have long section titles, this template takes care of double spacing the lines in the title. If the title is long to fit in the table of contents, the template will single space the title.

3.1 Yet Another Table

Another table is placed here to show the effect of having tables in multiple sections. The list of tables should still double space between table titles, while single spacing long table titles.

Dates	Attendance
August 8-10, 2008	3,523
August 14-16, 2009	4,003
July 9-11, 2010	5,049
August 5-7, 2011	6,891
August 10-12, 2012	9,464
August 16-18, 2013	11,077
July 18-20, 2014	14,686
July 31-August 2, 2015	18,411

Table 3.1: San Japan attendance. Data is taken from [**?**]. I intentionally make the title of this table long so the single space effect is seen in the list of tables.

You may be wondering why San Japan was chosen. There are a few reasons as to why I did this:

1. It is one of the fastest-growing anime conventions in Texas.

2. Filler.

3. I wanted a good variety of table examples.

4. Because conventions are cool.

The *enumerate* environment was used to generated an ordered list above.

3.2 Section Test Example

We insert another figure here, just for kicks.

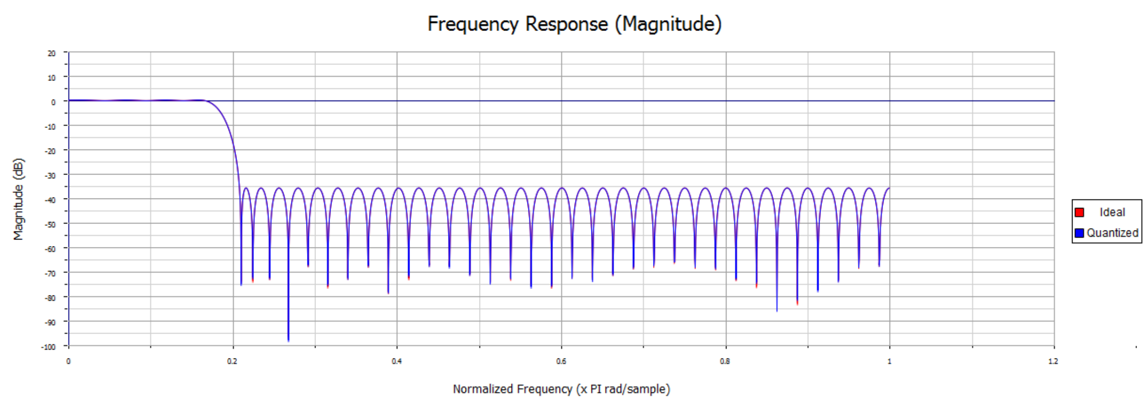


Figure 3.1: A low pass filter design.

3.2.1 Filler, Filler, Filler

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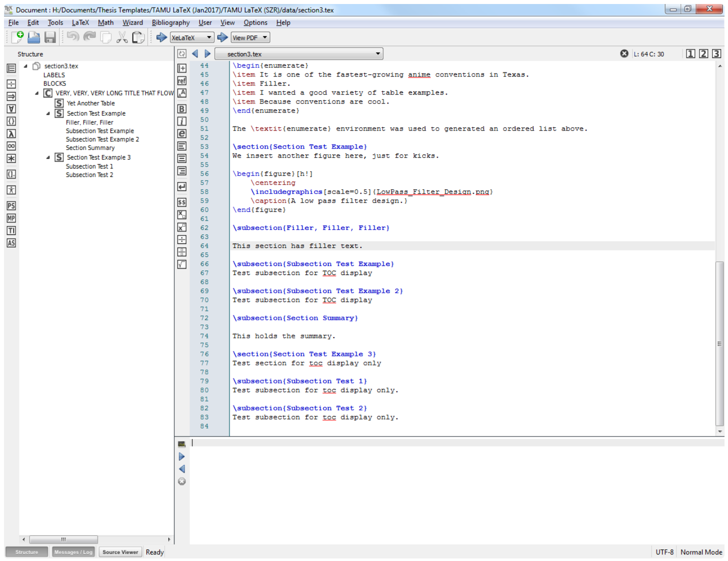

Figure 3.2: A typical Texmaker workspace in Windows 7. The right sidebar displays the current file's structure according to the subsections in place.

few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document.

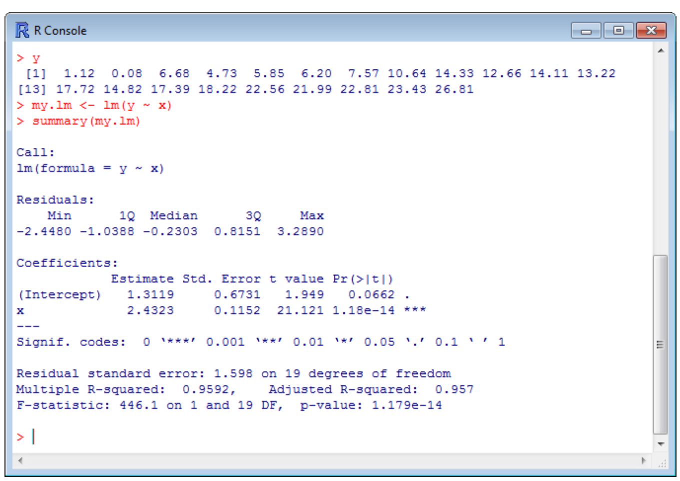

Figure 3.3: Some commands in R.

3.2.2 Subsection Test Example

Test subsection for TOC display

3.2.3 Subsection Test Example 2

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Figure 3.4: The logo of a familiar university.

3.2.4 Section Summary

This holds the summary. Well, not really a summary - there was a lot of filler in this section.

Figure 3.5: Yet another blank float that has no purpose. This is only to test the appearance of the Lists of Figures and the List of Tables.

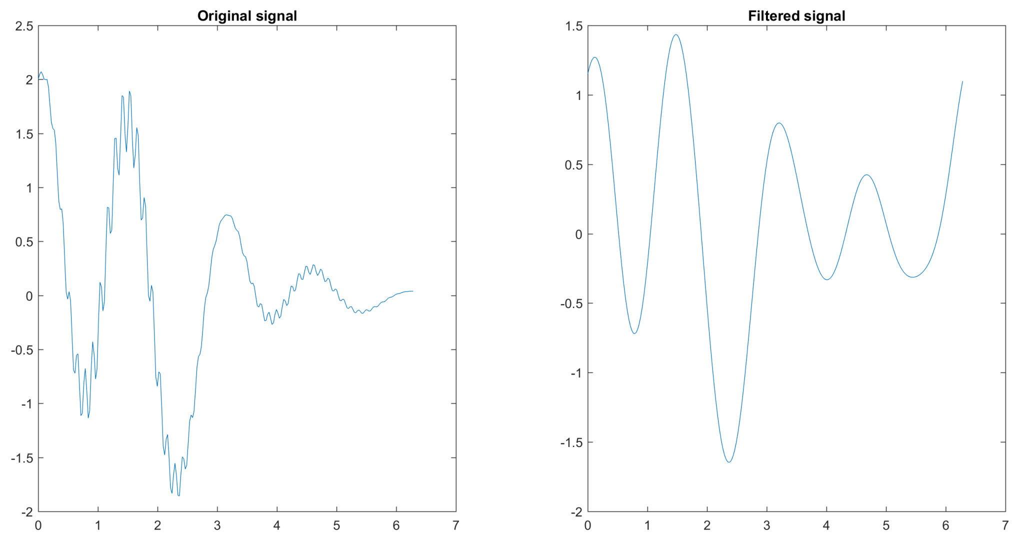


Figure 3.6: A signal and the result after a basic filter. The FFT was used to create the plot on the right.

3.3 Section Test Example 3

Test section for toc display only.

Figure 3.7: There is nothing to see here.

Figure 3.8: There is another float here. I wonder what could be here? Guess what? Nothing! There is no material in this float.

3.3.1 Subsection Test 1

Test subsection for toc display only.

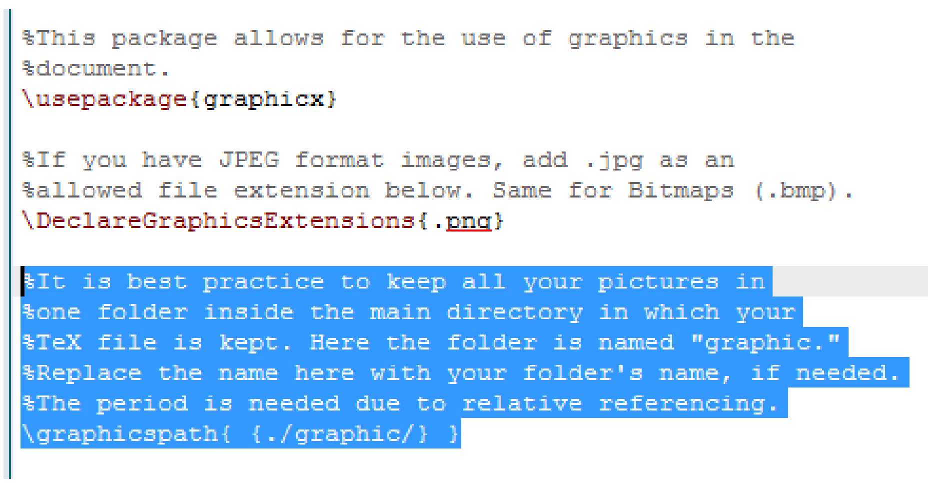
3.3.2 Subsection Test 2

Test subsection for toc display only.

4. SUMMARY AND CONCLUSIONS

The summary goes here, along with your conclusions. The title of this final chapter/section must contain the words “summary” or “conclusions.”

Here, I attempt to fill the section with more figures, possibly more tables. The inclusion of these floats is to manipulate the list of figures and list of tables in order to see when the inconsistent spacing begins. It is important to remember that any images you wish to use are placed in the appropriate directory inside the folder in which the project is kept. In the original template, all the images used as figures here are placed in the subdirectory *graphics*, as declared in the preamble of *TAMUTemplate.tex*. If you wish to use any other directories, be sure to declare them in the preamble of *TAMUTemplate.tex*. See the figure below on how to declare directories.



```
%This package allows for the use of graphics in the
%document.
\usepackage{graphicx}

%If you have JPEG format images, add .jpg as an
%allowed file extension below. Same for Bitmaps (.bmp).
\DeclareGraphicsExtensions{.png}

%It is best practice to keep all your pictures in
%one folder inside the main directory in which your
%TeX file is kept. Here the folder is named "graphic."
%Replace the name here with your folder's name, if needed.
%The period is needed due to relative referencing.
\graphicspath{ {./graphic/} }
```

Figure 4.1: Declaring graphics directories.

This version of the template now has a section to place any packages that you are using - see the figure below.

More figures will be inserted, with some text between them.

This section has filler text. These words serve no meaning except to fill a few lines in the

```
%For figures and tables.
\usepackage{float}

%To customize captions in floats.
\usepackage{caption}



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Please place all your personal packages here. Check to
%see if the packages you wish to use are not already
%declared above. Placing all your personal packages
%here allows me to determine if there are any package
%issues in compilation, as well as any conflicts
%that may arise by the order of loading.
%--Sean Zachary Roberson
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Begin student defined packages.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%End student defined packages.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure 4.2: The place to declare any packages you require that I have not already declared. This simplifies debugging.

document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document. This section has filler text. These words serve no meaning except to fill a few lines in the document.

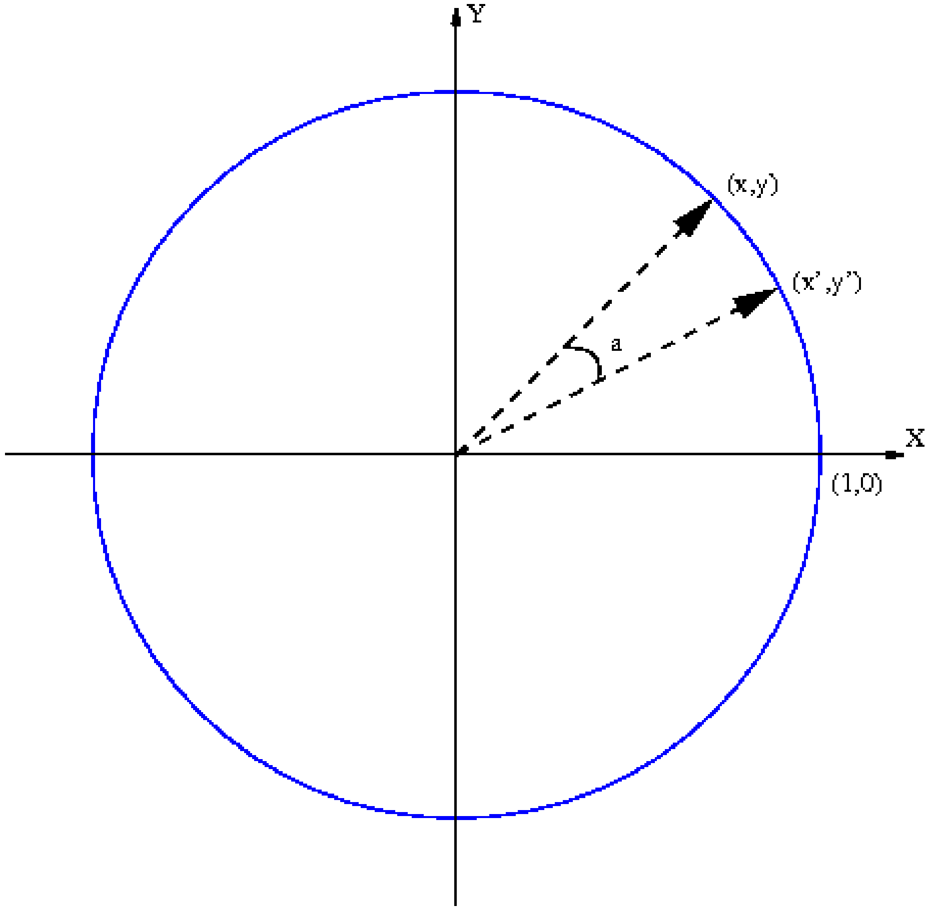


Figure 4.3: Two points on the unit circle and their corresponding position vectors.

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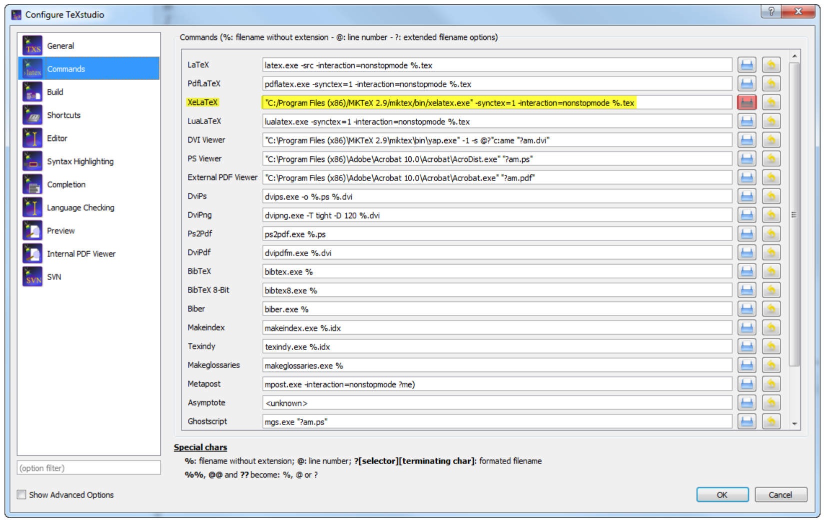

Figure 4.4: Changing the method of compilation for XeLaTeX in TeXstudio.

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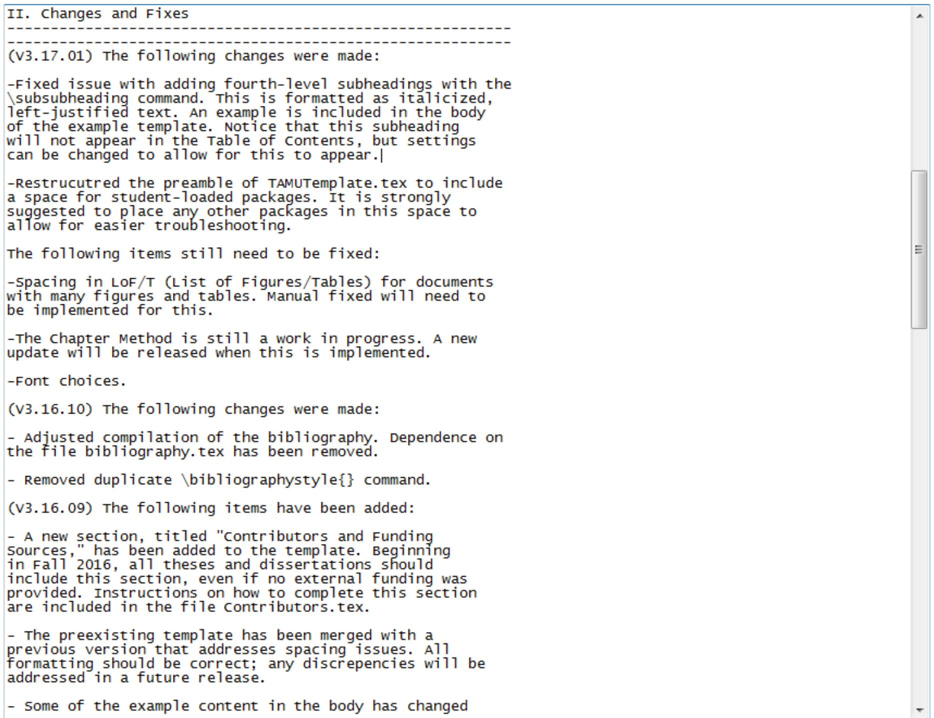

```
II. Changes and Fixes
----------------------------------------------------------
----------------------------------------------------------
(v3.17.01) The following changes were made:

-Fixed issue with adding fourth-level subheadings with the
\subsubheading command. This is formatted as italicized,
left-justified text. An example is included in the body
of the example template. Notice that this subheading
will not appear in the Table of Contents, but settings
can be changed to allow for this to appear.

-Restrucutred the preamble of TAMUTemplate.tex to include
a space for student-loaded packages. It is strongly
suggested to place any other packages in this space to
allow for easier troubleshooting.

The following items still need to be fixed:

-Spacing in LoF/T (List of Figures/Tables) for documents
with many figures and tables. Manual fixed will need to
be implemented for this.

-The Chapter Method is still a work in progress. A new
update will be released when this is implemented.

-Font choices.

(v3.16.10) The following changes were made:

- Adjusted compilation of the bibliography. Dependence on
the file bibliography.tex has been removed.

- Removed duplicate \bibliographystyle{} command.

(v3.16.09) The following items have been added:

- A new section, titled "Contributors and Funding
Sources," has been added to the template. Beginning
in Fall 2016, all theses and dissertations should
include this section, even if no external funding was
provided. Instructions on how to complete this section
are included in the file Contributors.tex.

- The preexisting template has been merged with a
previous version that addresses spacing issues. All
formatting should be correct; any discrepencies will be
addressed in a future release.

- Some of the example content in the body has changed
```

Figure 4.5: A portion of the changelog in the README for this document. This is located in the root directory.

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4.1 Challenges

Section here is to test toc display only.

4.2 Further Study

Section here is to test toc display only.

REFERENCES

[1] "Animecons.com - Anime Conventions and Guests." Web, 2015.

[2] N. Carothers, *Real Analysis*. Cambridge University Press, 2000.

[3] A. Einstein, "Zur Elektrodynamik bewegter Körper. (German) [On the electrodynamics of moving bodies]," *Annalen der Physik*, vol. 322, no. 10, pp. 891–921, 1905.

[4] C. F. Barnes and R. L. Frost, "Residual vector quantizers with jointly optimized code books," *Advances in Electronics and Electron Physics*, vol. 84, pp. 1–59, 1992.

[5] G. T. Gilbert and R. L. Hatcher, "Wagering in final jeopardy!," *Mathematics Magazine*, vol. 67, pp. 268–277, October 1994.

[6] "Results - Arcadia Festival of Bands." Web, November 2011.

APPENDIX A

FIRST APPENDIX

Text for the Appendix follows.

Figure A.1: TAMU figure

APPENDIX B

A SECOND APPENDIX WHOSE TITLE IS MUCH LONGER THAN THE FIRST

Text for the Appendix follows.

Figure B.1: Another TAMU figure.

B.1 Appendix Section

B.2 Second Appendix Section