This Dissertation

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Search for lepton flavor violating decays

of Higgs Bosons

with the CMS experiment

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Search for lepton flavor violating decays

of Higgs Bosons

with the CMS experiment

A Dissertation

Submitted to the Graduate School

of the University of Notre Dame

in Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in

Physics

by

Nabarun Dev,

Colin Philip Jessop, Director

Graduate Program in Physics

Notre Dame, Indiana

October 2018

Search for lepton flavor violating decays

of Higgs Bosons

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Abstract

by

Nabarun Dev

Please note that the full LaTeX source code (and an associated `Makefile`) is available from the University of Notre Dame Graduate Student Union web site. The Information Technology Committee page[1] has all the necessary files in download-able form. This particular dissertation was developed under Unix, but is also be usable under Windows with the appropriate LaTeX setup and was modified on a Windows system in 2012-2013. It should also work with on Mac.

While the source code for this document provides an excellent example for how to use the NDdiss2$_\varepsilon$ LaTeX class to write a Notre Dame thesis, it is *not* a substitution for the documentation of the NDdiss2$_\varepsilon$ LaTeX class (also available on the ND GSU web site).

In this thesis, I will tell all that I know about Gnus. Gnus are wonderful little creatures that inhabit the center of the earth and give us wonderful and plentiful trees, dirt, and other earthly-things.

In short, we should love and cherish the Gnus. They can be very friendly, and are often mistaken for squirrels on the University of Notre Dame campus. Feed

[1] `http://www.gsu.nd.edu/`

them whenever possible. If they get caught in trash cans, tip them over so that they can get out.

This abstract is going to continue on, including a few formulas, just for the sake of spilling over on to two pages so that we can see the author's name in the top right corner:

$$
\begin{aligned}
a^2 + b^2 &= c^2 \\
E &= mc^2 \\
\frac{e}{m} &= c^2 \\
a^2 + b^2 &= \frac{e}{m}
\end{aligned}
$$

These equations, by themselves mean nothing. But to the common Gnu, they define a whole way of living. While intricate mathematical implications certainly do not infiltrate the majority of humans' lives, every Gnu, from birth, is imbued with a sense of mathematical certainty and guidance. All Gnus, great and small, feel at one with mathematics. The cute furry bit is just a scam for their calculating minds.

Dedicated to

To my family

CONTENTS

FIGURES

TABLES

PREFACE

I would like to preface this work with all the wonderful things that Gnus have brought to our society: trees, dirt, flowers, grass, lakes, and other earthly-things. We should not forget them in our daily lives.

Additionally, we should offer them food for all their hard work. In fact, Gnus work so hard that they sleep for the colder half of the year. As such, they tend to grow a little rotund. Humans should not fault them for this, as it is necessary for their survival. Indeed, many humans grow rotund on their on accord!

ACKNOWLEDGMENTS

I would like to acknowledge all the loving Gnus at Notre Dame. Particularly the one that comes to the window in the Hayes Healy building. He (she?) has given me much inspiration, love, and dirt. I would also like to thank my advisor, Dr. Gary Greenfield, with whom this work would not have been possible.

Finally, I would like to thank the U.S. Government, Department of Gnus, for their generous grant, number GNU3042920920.3, which allowed me to pursue my work.

SYMBOLS

$\mathcal{F}$	sighting frequency of Gnus about campus
p	student population
f	type of food available
d	day of week
c	speed of light
m	mass
e	elementary charge
a, b	miscellaneous constants
E	energy

Features of Formatting in This Example File

This `chapter` has been added to the original sample file to highlight the various features with the formatting that conforms to the Graduate school guidelines — whether obtained due to the use of NDdiss2$_\varepsilon$ class file or just plain good practice.

- An important note on line-breaks via `\\` in titles: the titles of the thesis as well as chapters and table captions use `\MakeTextUppercase{}` from the `textcase` package. Due to the nature of the `center` environment, any line-breaks introduced in titles and captions should be protected, as in `\protect\\`. To preserve the case in titles and captions, use, e.g., `\NoCaseChange{Gnus}`.

- In the *dedication*, the title name has been modified. So, you know how to and that it can be done.

- The entries in the *List of figures* and *List of Tables* are single-spaced themselves but are double-spaced from the other.

- The table captions are not in all CAPS as well for the reason mentioned above.

- Appropriate space is left between the `Table xx` and its corresponding caption (which is double-spaced itself) as in table **??**.

- Tables look much better without the vertical lines (good practice).

- There is double-spacing between the table entries but single-spacing within the entry.

- The chapter (see Chapter **??**) or section titles are double-spaced as mentioned in the guidelines.

- There is a `subsubsection` present (eg. section **??**) and is properly formatted in the TOC.

- Sections deeper than `subsubsection` should not appear in the TOC.

- Table A.1 is an example of the use of landscape environment in which a normal table is formatted in a *landscape* mode.

- The longtable environment is used in Tables 3.1 and A.2, in normal and `landscape` mode, respectively. The table captions are formatted properly in both cases.

- In the table 3.1, the `footnote` in the table header does not appear at all. This is not an error of the NDdiss2_ε class but of the longtable package.

- An example of citing a website is shown in the bibliography (see [**?**]) which is formatted using the `nddiss2e.bst` citation style file.

- A bit of information on the NDdiss2_ε class file and the typesetting program used is included in a box on the last page of the thesis.

- Footnotes should space properly.

- Items in `itemize`, `enumerate`, and `description` environment should automatically single-space within an item, but double space between items.

CHAPTER 1

Introduction

The standard model of particle physics is the most complete description of nature available today. The discovery of the Higgs Boson added another feather to the hat of the standard model...

...expand...

Besides confirming the mechanism by which particles acquire mass, this discovery has provided us a portal to look for and possibly study newer and exotic physics process. The search for such processes are generally referred to as search for physics beyond the standard model (BSM). One such interesting class of processes is those in which lepton flavor is violated in interactions involving charged leptons. In particular the decay of the Higgs into charged leptons ofdifferent flavor is forbidden by the SM if the theory is to be renormalizable. However, if the cut-off scale is finite such process can occur. Further many beyond the standard model extensions allow for such processes. These include susy models, randal-sundrum models, 2 HDM models. This interactions could be a strong indicator of new physics providing us with a strong motivation to perform searches looking for them.

..expand..

This thesis describes a search for lepton flavour violating decays of the SM Higgs boson followed by a search for.... In both cases the search is performed in a channel where the Higgs decays via a lepton flavor violating interaction into a muon and a tau lepton with the tau lepton subsequently decaying to an electron....

...expand...

The search is performed with data collected by the CMS detector at the LHC experiment. The results presented here build on and improve resultd from all such searches performed in the past.

CHAPTER 2

Theoretical bases

2.1 The Standard Model

So why do gnus do what they do? This is a perennial question that has yet to be answered definitively by scientists. Is their future somehow tied inexplicably with that of humans? Hard to say, but we do feed them a lot. It has even been theorized that rotundness is a symbol of status or class within the Gnus; those who are more productive (i.e., cute, furry, friendly) will be fed more than those who are less so. So the more rotund, the higher status one has in the Gnu society.

One could extrapolate this to mean that there is a super-Gnu out there somewhere; the biggest, rotundest Gnu that you've ever seen, probably of epic proportions! This would have to be the Leader of Gnus, or LoG for short. But the LoG would definitely have to be the cutest, furriest, and most friendly Gnu that you've ever seen.

2.1.1 The LoG

So how does the LoG get chosen? Ultimately by humans. So we can say that the Gnu society is perhaps the truest democracy that has ever existed; the leader is chosen by merit, and chosen by complete outsiders. As such, the LoG must truly epitomize all that Gnus stand for: opposedness to overmanagement, cuteness, friendliness, and furriness [**?**]. The gnus themselves vote at an anual election, based upon these attributes (campagaining is an anethema to Gnus; see Section **??**).

2.2 Physics beyond the standard model

Table 3.1 shows the latest electoral college voting by the LoG for the year 2000. Each Gnu is scored on a scale of one to ten on the attributes described above. The results shown in the table are average scores in each category for all votes; the Gnu's final score is shown in the final column.

TABLE 2.1

Electoral College Results for the LoG Election in the Year 2000

Candidate[1]	Anti-management	Cuteness	Friendliness	Furriness	Aggregate
Glen	6.2	7.0	6.1	9.8	7.2
Goober	6.9	2.1	5.7	4.1	4.6
Genevra	2.2	2.0	1.1	1.1	1.6
Greg	8.3	0.4	1.1	9.5	4.8
Gina	6.0	7.8	6.4	4.9	6.2
Geof	1.1	8.7	3.7	7.3	5.2
Grendel	2.8	1.7	3.4	3.2	2.7
Geronimo	1.2	1.2	8.8	2.2	3.3
Gabrielle	4.7	3.6	0.8	2.0	2.7
Giovani	8.4	5.8	3.4	7.4	6.2

TABLE 2.1

Continued

Candidate	Anti-management	Cuteness	Friendliness	Furriness	Aggregate
Graham	4.7	5.8	5.3	0	3.9
Gil	5.9	4.0	5.5	7.6	5.7
Gerald	2.0	3.7	8.0	4.3	4.5
Guilani	7.7	3.9	2.7	6.4	5.1
Guido	7.6	4.3	6.5	1.0	4.8
Godzilla	5.1	2.2	5.3	6.9	4.8
Gail	5.7	7.9	4.1	1.0	4.6
Garth	4.7	7.1	2.5	3.0	4.3
Gavin	1.1	9.5	0.4	8.0	4.7
George	9.5	4.5	9.1	7.5	7.6
Gunnar	1.4	5.8	4.8	6.2	4.5
Gillian	7.6	9.0	6.4	4.6	6.9
Greta	1.5	0.5	0.9	7.7	2.6
Gabby	1.2	3.3	7.0	2.1	3.4
Gaetena	6.8	1.9	4.1	8.3	5.2
Ganet	2.3	1.1	8.5	7.3	4.8
Gardenia	1.8	9.5	9.9	3.0	6.0
Genna	5.2	3.7	3.4	3.8	4.0
Genesis	1.7	8.3	6.7	4.9	5.4
Genaveve	4.7	8.9	3.4	9.2	6.5

TABLE 2.1

Continued

Candidate	Anti-management	Cuteness	Friendliness	Furriness	Aggregate
Gene	3.3	6.9	0.6	5.5	4.0
Gilda	5.2	4.6	9.9	1.4	5.2
Goldie	8.9	9.1	2.0	8.2	7.0
Grace	5.9	3.2	3.1	4.3	4.1
Gretchen	4.5	6.5	1.6	1.3	3.4
Garrick	4.8	5.7	9.4	5.1	6.2
Gallagher	7.4	0.4	7.6	0.4	3.9
Gerry	1.4	8.8	4.7	0.5	3.8
Gertrude	9.1	8.3	0.4	5.5	5.8
Gehosephet	6.6	2.9	8.3	4.4	5.5
Gohn	8.7	2.6	7.4	2.3	5.2
Gibby	8.7	6.9	4.7	7.2	6.9

As you can see from Table 3.1, George (my favorite Gnu) won for the year 2000, with an aggregate score of 7.6.

CHAPTER 3

Experimental Setup

..intoduce...

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a powerful proton-proton synchrotron. It was built and is operated at the European Center for Nuclear Research (CERN) and is situated about 100 m underground close to Geneva, Switzerland. It has a circumference of 26.7 km and uses a tunnel previously built for LEP (Large Electron Positron Collider). Being a particle-particle collider, it consists of two rings with counterrotating beams which are steered using magnets and accelerated using radiofrequency resonating cavities. These beams are made to intersect at four collision points around the LHC ring, at one of which rests the CMS detector. Besides proton-proton collisions the LHC can also collide heavy ions (lead-lead collisions) or heavy ions with protons (lead-proton collisions). Since starting operation in September 2008 the LHC has been the world's most powerful apparatus and will probably remain so in the forseeable future. The following section describes proton-proton collisions at the LHC as the data used in the subsequent physics analysis corresponds to events from these collisions.

The injector chain that supplies protons to the LHC consists of four CERN accelerators that actually predate the LHC: Linac 2, PSB (Proton Synchroton

Booster), PS (Proton Synchotron) and SPS (Super Proton Synchotron). This is illustrated in figure **??**. The proton source is simply a tank of hydrogen gas. The hydrogen atoms are ionized to yield protons which are then fed in to the Linac 2, a linear accelerator. This accelerates the protons to an energy of about 50 MeV which are then fed into a series of circular accelerators starting with the PSB which accelerates the protons to 1.4 GeV. The PS then accelerates them to 25 GeV, and they are then sent to the SPS which accelerates them to 450 GeV before being finally fed into the LHC beampipe. Inside the LHC the protons are accelerated by sixteen radiofrequency cavities which are made to oscillate at 400 MHz and the proton beam is sorted into discrete packet called 'bunches'. The beam is steered by 1232 Niobium-Titanium superconducting dipole magnets and collimated using quadrupole magnets. This magnet system is kept at a temperature below 2 K, using a pressurised bath of superfluid helium at about 0.13 MPa, and operates at fields above 8T. The LHC has three sophisticated vacuum systems: the insulation vacuum for cryomagnets, the insulation vacuum for helium distribution, and the beam vacuum.

It takes about 4 minutes and 20 seconds to fill up each of the LHC rings wih protons, and about 20 minutes for the proton beam to reach its current peak energy of 6.5 TeV. At this point, each LHC beam contains 2808 bunches with 1.5×10^{11} protons per bunch, colliding at a center of mass energy (COM) of 13 TeV. It is anticipated for the COM energy to increase to 14 TeV in 2018. Looking for physics beyond the standard model by colliding protons at such high energies is one of the primary aims of the LHC.

Another important parameter for a collider like the LHC is the instantaneous luminosity (referred to as just luminosity in the following), $\mathscr{L}$. The number of events (N) generated per second for some processes is given by:

$$\frac{dN}{dt} = \sigma \mathscr{L} \tag{3.1}$$

where σ is the cross-section of the processes. The luminosity of the LHC can be also expressed in terms of only beam parameters as:

$$\mathscr{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \tag{3.2}$$

where N_b is number of protons in a bunch, n_b is number of bunches per beam, f_{rev} is the revolution frequency, γ_r the relativistic gamma factor, ϵ_n the transverse beam emittance, β^* the beta function at the collision point, and F is a reduction factor coming from the fact that the beams cross at an angle.

This luminosity intergrated over time represents the total number of events collected per unit cross section and is called the integrated luminosity (L).The LHC has already reached its nominal design luminosity of $10^{34} cm^{-2} s^{-1}$, and it has delivered data amounting to a more than $36 fb^{-1}$, only in 2016. Figure 3.1 shows the amount of data delivered by the LHC overlaid with the subset collected by the CMS detector in 2015 and 2016.

In the longer term, it is planned to keep the LHC running, punctuated with several scheduled stops for upgrades and maintenance, at least until late 2030s. During this period it is anticipated to operate at increasingly higher luminosities helping collect unprecedented amounts of data. Figure 3.2 shows an overview of the long term LHC schedule.

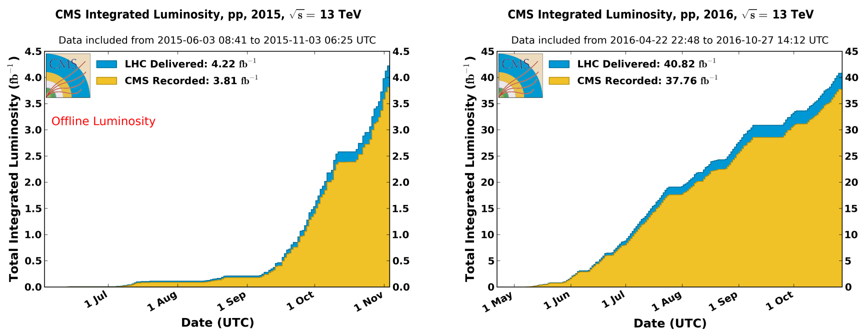

Figure 3.1: Evolution of integrated luminosity in 2015 and 2016 delivered by LHC (blue), and collected by CMS detector (orange).

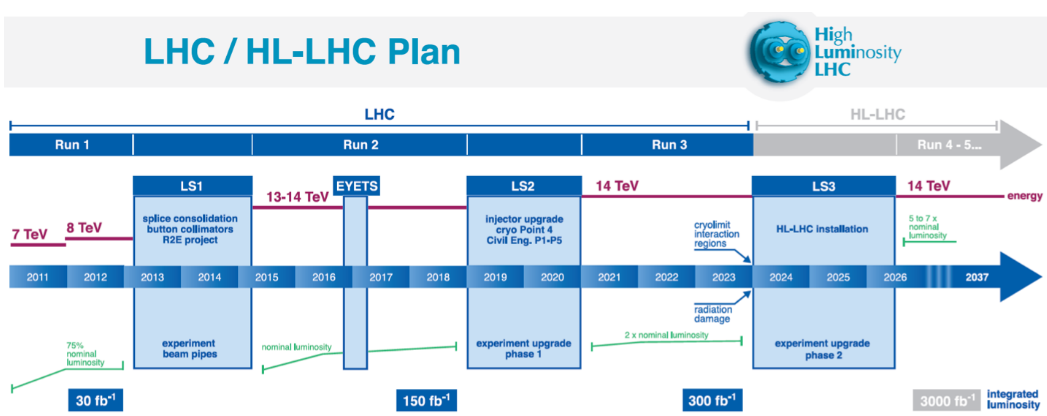

Figure 3.2: Overview of the long term LHC schecdule.

3.2 The CMS Detector

The Compact Muon Solenoid is a general multipurpose particle physics detector that is placed in one of the four collision points of the LHC. It is 28.7m long with a diameter of 15.0m, weighs 14000 tons and is composed of several subdetectors. Its aim is to study a broad array of physics, from making precise measurements of known processess to searches for exotic processes predicted by a multitude of BSM theories. In order to be able to pursue its physics aims at the challenging LHC conditions, the CMS experiment needs to meet several requirements which primarily include good muon identification and momentum resolution over a wide range of momenta and angles, good dimuon mass resolution, good charged-particle momentum resolution and reconstruction efficiency, good electromagnetic energy resolution, good diphoton and dielectron mass resolution, good missing-transverse-energy and dijet-mass resolution. The backbone of the CMS is a superconducting solenoid that houses its tracking and calorimetry systems and provides an axial magnetic field of 3.8T. The inner-most layer is the silicon pixel and strip tracker that measures the trajectories of charged particles. Surrounding the tracker are the lead tungstate crystal electromagnetic calorimeter (ECAL) which measures the energy of electrons and photons, and the hadronic calorimeter (HCAL) which measures the energy of heavier particles that pass through the ECAL. The ECAL also contains a preshower detector for extra spatial precision. Outside the solenoid is the muon system which has gas-ionization detectors placed in the steel yoke of the magnet. This is the outermost component of CMS and measures the momenta of muons that traverse through it. A sophisticated two-level trigger system that helps filter out a small fraction of most interesting events among millions produced at the LHC also forms a vital

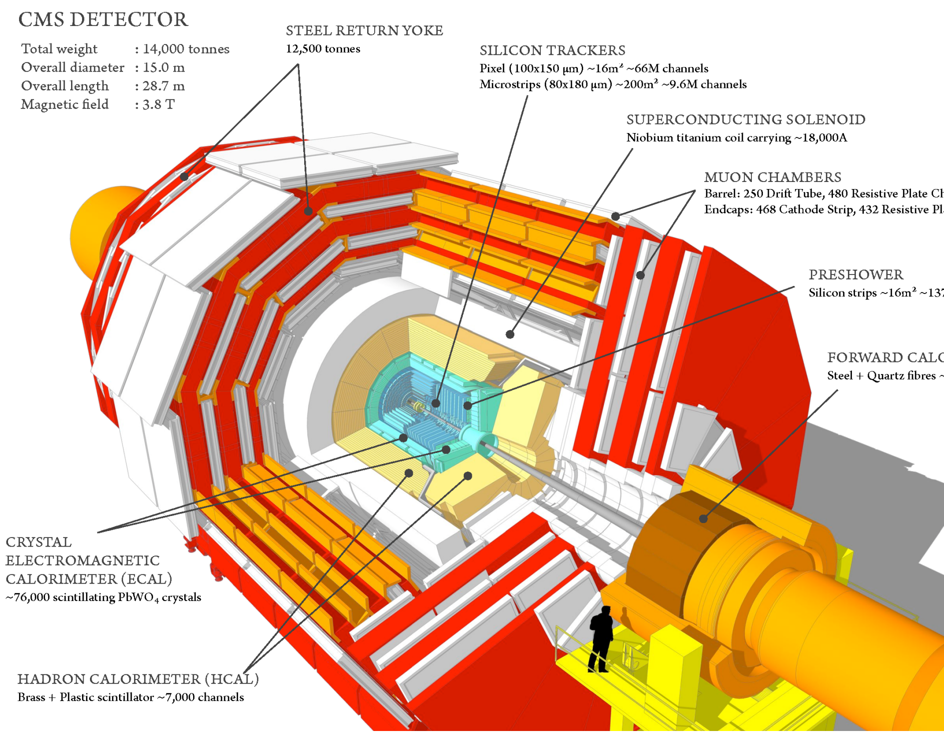

Figure 3.3: Layered View of the CMS detector

part of the CMS.The powerful solenoid, sophisticated muon system and its compact design (given its complexity) give CMS its name. Figure 3.3 shows a layered view of the detector. The following sections describe it in further detail.

3.2.1 Coordinate Conventions

The CMS detector has adopted a right-handed coordinate system, the origin of which lies at the nominal collision point inside the experiment.The x-axis points radially inward towards the center of the LHC while the y-axis points vertically upwards. This makes the z-axis point along the beam direction. At point 5 of LHC (a village named Cessy in France) where the CMS is, the z axis points toward the Jura Mountains. In cylindrical co-ordinates, the polar angle θ is measured from the z-axis while the azimuthal angle ϕ is measured from the x-axis in the x-y plane. The polar angle is used to define the pseudo-rapidity $\eta = -ln(tan(\frac{\theta}{2}))$ which is a close approximation for rapidity if $E \gg m$. The rapidity is a Lorentz invariant quantity under boosts in the z-direction. Since it is typical of particles that CMS sees to have $E \gg m$, the Lorentz invariance approximately holds for pseudo-rapidity as well.

3.2.2 Charged Particle Tracking System

So why do gnus do what they do? This is a perennial question that has yet to be answered definitively by scientists. Is their future somehow tied inexplicably with that of humans? Hard to say, but we do feed them a lot. It has even been theorized that rotundness is a symbol of status or class within the Gnus; those who are more productive (i.e., cute, furry, friendly) will be fed more than those who are less so. So the more rotund, the higher status one has in the Gnu society.

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Greg	8.3	0.4	1.1	9.5	4.8
Gina	6.0	7.8	6.4	4.9	6.2
Geof	1.1	8.7	3.7	7.3	5.2
Grendel	2.8	1.7	3.4	3.2	2.7
Geronimo	1.2	1.2	8.8	2.2	3.3
Gabrielle	4.7	3.6	0.8	2.0	2.7
Giovani	8.4	5.8	3.4	7.4	6.2

TABLE 3.1

Continued

Candidate	Anti-management	Cuteness	Friendliness	Furriness	Aggregate
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Gail	5.7	7.9	4.1	1.0	4.6
Garth	4.7	7.1	2.5	3.0	4.3
Gavin	1.1	9.5	0.4	8.0	4.7
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Gabby	1.2	3.3	7.0	2.1	3.4
Gaetena	6.8	1.9	4.1	8.3	5.2
Ganet	2.3	1.1	8.5	7.3	4.8
Gardenia	1.8	9.5	9.9	3.0	6.0
Genna	5.2	3.7	3.4	3.8	4.0
Genesis	1.7	8.3	6.7	4.9	5.4
Genaveve	4.7	8.9	3.4	9.2	6.5

TABLE 3.1

Continued

Candidate	Anti-management	Cuteness	Friendliness	Furriness	Aggregate
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Goldie	8.9	9.1	2.0	8.2	7.0
Grace	5.9	3.2	3.1	4.3	4.1
Gretchen	4.5	6.5	1.6	1.3	3.4
Garrick	4.8	5.7	9.4	5.1	6.2
Gallagher	7.4	0.4	7.6	0.4	3.9
Gerry	1.4	8.8	4.7	0.5	3.8
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Gehosephet	6.6	2.9	8.3	4.4	5.5
Gohn	8.7	2.6	7.4	2.3	5.2
Gibby	8.7	6.9	4.7	7.2	6.9

As you can see from Table 3.1, George (my favorite Gnu) won for the year 2000, with an aggregate score of 7.6.

CHAPTER 4

Object reconstruction and event generation

CHAPTER 5

Statistical and Machine Learning techniques

CHAPTER 6

Search for LFV decays of h125

This chapter describes the analysis in search for lepton flavor violating decay of the h125 boson into a muon and an electronically decaying tau-lepton. The theoretical motivation for this search is discussed in the introduction and theory sections. In the following sections the dataset and MC samples used, event selection and subsequent analysis strategy, systematic uncertainties affecting the analysis and finally the results are described in detail.

CHAPTER 7

Search for LFV decays of heavy Higgs

CHAPTER 8

Results

APPENDIX A

GNU GENERALISMS

A.1 Definitions

Several definitions are presented in Table A.1 to show both how to do rotated, line-spanning tables, as well as to define some commonly used Gnu terms.

TABLE A.1

Commonly used Gnu Terms

Term	Definition
Gnu	Small furry animal that is related to the squirrel (although they won't admit it).
LoG	Abbreviation for the "Leader of Gnus". See Chapter **??**.
Twizzlers	Red, twisty candy that is among the most favorite of Gnu foods. Gnus frequently appear overly cute and friendly to humans bearing twizzler packages. This is known as "trolling for twizzlers" among the Gnus.

Finally, Table A.2 shows the top ten Gnus from Table 3.1 ranked in order by their aggregate score (along with some of the raters' comments). This follows a long-standing Gnu tradition of self-improvement through public announcement of score (which some associate with military origins [**?**]). Indeed, this very table has been observed in the Gnu lodge where it was posted for peer review [**?**].

TABLE A.2

Top Ten Gnus From Table 3.1 With Reviewer Comments.

Gnus are Listed Below in Alphabetic Order.

Candidate	Aggregate score	Reviewer Comments
George	7.6	George is an excellent candidate for the LoG. Slightly low C, but hopefully, this 7.6 will be high enough!
Glen	7.2	A little weak on AM and Fr, but good scores overall. One or two more years of experience should be enough.
Goldie	7.0	Dismal score in Fr; suspect it had something to do with strenuous weight loss program this past year.
Gillian	6.9	Excellent C, but a little shabby on the Fu. Suggest more roughage.
Gibby	6.9	Reasonable scores, but need to work on Fr. Gibby is definitely not a morning Gnu.
Genaveve	6.5	Very low Fr; perhaps more coffee? Suggest practicing "cute faces" in the mirror several hours per day.
Giovani	6.2	Very low Fr; suspect hanging out with Genaveve too much.

TABLE A.2

Continued

Candidate	Aggregate score	Reviewer Comments
Gina	6.2	Mediochre Fu, somewhat low AM. Perhaps a future in marketing or advertising?
Garrick	6.2	Fairly low AM. Fu could be better as well; buy a comb. And a mirror. Immediately.
Gardenia	6.0	Dismal AM; very low Fu. Seems to care more about meeting agendas than personal appearance.

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