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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

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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 page¹ 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 ϵ` \LaTeX class to write a Notre Dame thesis, it is *not* a substitution for the documentation of the `NDdiss2 ϵ` \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:

$$a^2 + b^2 = c^2$$

$$E = mc^2$$

$$\frac{e}{m} = c^2$$

$$a^2 + b^2 = \frac{e}{m}$$

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

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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 ϵ` 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 1.1.
- 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 2) or section titles are double-spaced as mentioned in the guidelines.

- There is a `subsubsection` present (eg. section 2.1.1.1) 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 2.1 and A.2, in normal and *landscape* mode, respectively. The table captions are formatted properly in both cases.
- In the table 2.1, 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

1.1 Overview

This is an overview of the introduction. In here, I will use many many buzzwords and other legalistic-types of terms, mostly beginning on the expounding of the holistic and synergistic energy that Gnus bring to our organizations.

1.1.1 Background

In preparation for reading this dissertation, I would highly recommend reading some of the other material available on Gnus [? ?]. They are very well written and will give you a fuller understanding of Gnus.

Gnus are frequently mistakes for squirrels. They are not squirrels. They are Gnus. Don't call them squirrels, either (unless you have food in your hand); they tend to get a bit upset.¹ If you have food in your hand, they tend to ignore this insult and accept your food as a peace offering.²

1.1.2 Foreground

Table 1.1 shows some feeding frequencies for where Gnus like to eat around the Notre Dame campus. Gnus have work weeks, just like humans do, hence the much

¹This is frequently mistaken for the chattering and scampering away. Gnus are actually quite polite; they will leave if they have nothing nice to say, for fear of saying something offensive.

²Sometimes they'll follow you if you continue to refuse to feed them.

TABLE 1.1

Where Gnus Like to eat

Location	Sun	Mon	Tue	Wed	Thu	Fri	Sat
Front of Dome	1	5	6	5	4	5	1
Stonehenge	2	9	10	12	9	14	2
The Rock	1	3	4	3	4	3	0
The ACC	3	4	5	5	5	4	1
Dining Halls	5	14	12	13	14	12	3
Hesburgh Library	2	3	5	2	3	4	2

lower frequencies on weekends. This can lead us to conclude that Gnu weekend shifts are much smaller than the normal work-week shifts. In fact, we can attempt to parametrize the sighting frequency, \mathcal{F} , by the student population, type of food, and day of the week as:

$$\mathcal{F} = \mathcal{F}(p, f, d). \quad (1.1)$$

Table 1.2 shows what they typically like to eat.

Figure 1.1 shows a nice graph of location distributions by day of week. I have no real reason for including it except to show that figures work as well. Did I mention that Gnus are really cool?

Gnus typically tend to come out when there are large gatherings of humans with food. Gnus work very hard at providing us with all the things that we like (trees, dirt, air, etc.), and so we should freely give them food. They will come

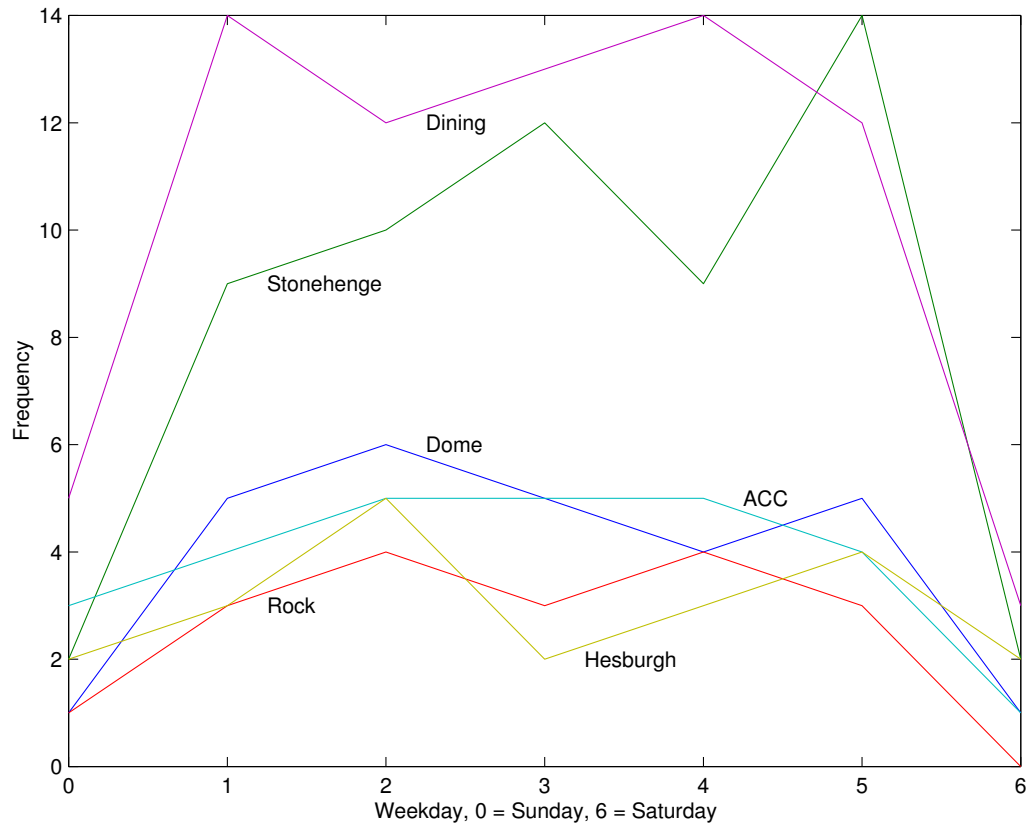


Figure 1.1. Location distributions by day of where, where the X axis is the weekday (0 through 6), and the Y axis is the sighting frequency

TABLE 1.2

What Gnus like to eat on the Notre Dame Campus,
Listed by Average Number of Sightings per Weekday

Food	Sun	Mon	Tue	Wed	Thu	Fri	Sat
Twinkies	1	5	6	5	4	5	1
Ding Dongs	2	9	10	12	9	14	2
Carrots	1	3	4	3	4	3	0
Lettuce	3	4	5	5	5	4	1
Twizlers	5	14	12	13	14	12	3
Jawbreakers	2	3	5	2	3	4	2

up and stand a respectful distance away from you, waiting to see if they will be rewarded for their efforts. If you offer some food, they will take it and back off a respectful distance in order to consume their food while leaving you to your “personal space.”

1.2 Groovin’ Gnus

Gnus do tend to stay away from humans in their normal day-to-day workings. This is mainly because humans don’t, for the most part, understand what they are doing. If a Gnu is working, and a human approaches it, the Gnu will tend to drop whatever it is doing and run away. This is probably do to the tendency for humans to have “group meetings” and “productivity seminars.” Most Gnus are deathly afraid of such overmanagement, and run at the slightest hint of it, for fear

that it will cripple their real work.

It is interesting, however, that Gnus have chosen an Institution of Higher Education for their BOO.³ It is often said that:

Academic politics are the dirtiest, meanest, ugliest, and generally the most low-down, in-your-face, and kick-em-while-they're-down than anywhere else (even Washington D.C.) because the stakes are so low.

It has been hypothesized that the Gnus are subtly trying to affect a change for the better (i.e., eliminating the overmanagement problems) by working the very system that they are trying to change, from within. That is, the graduates from Notre Dame can learn from the examples of the Gnus here, and run screaming (or chattering) at the slightest hint of overmanagement, and let the real work proceed unhindered.

³Base of Operations.

CHAPTER 2

Gnu Things are Good Things for all Graduate Students or so it Seems

2.1 Gnu See, Gnu Do, Gnu Goes Golfing with Green Golf Genes and Gesticulates Grapes

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 1.2).

2.1.1.1 Election Data

Table 2.1 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

TABLE 2.1

Continued

Candidate	Anti-management	Cuteness	Friendliness	Furriness	Aggregate
Giovani	8.4	5.8	3.4	7.4	6.2
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

TABLE 2.1

Continued

Candidate	Anti-management	Cuteness	Friendliness	Furriness	Aggregate
Genaveve	4.7	8.9	3.4	9.2	6.5
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 2.1, George (my favorite Gnu) won for the year 2000, with an aggregate score of 7.6.

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 2.
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 2.1 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 2.1 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	Mediocre 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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